DESCRIPTION

CHARACTERISTIC VALUE IDENTIFICATION METHOD
AND APPARATUS

Technical Field

The present invention relates to a characteristic value
identification method and an apparatus therefor, and in particular to a
characteristic value identification method and an apparatus therefor of
a part composing a product.

Background Art

There have been known two types of prior art characteristic value
identification methods and apparatuses therefor in the following:

One is disclosed in the Japanese Patent Application No.6-140081,
No.8-18946, No.9-287161, and the like. This prior art method adopts
means for identifying a natural frequency, a natural mode, and a
modal damping ratio based on measured data of a frequency response
function (FRF) obtained by a vibration test of a tested object (part).

The other is a method called a characteristic matrix identification
method. This method adopts means for identifying three kinds of
characteristic matrices, i.e. a mass matrix, a damping matrix, and a
stiffness matrix, which are coefficients of an equation of motion
formulated based on "equilibrium of forces" rule in a dynamics system,
from time history measured data of an exciting force and a response
obtained by the vibration test of the tested object (part).

Generally, a machine has a mechanical power source generating a
kinetic energy in some way, and is composed of a large number of parts
such as a mechanism which transmits the mechanical power and a
mechanism which takes advantage of the mechanical power for the
work. Also, with the parts composing the machine, parts based on a

1

physical unit system such as electric, mechanical, and fluid systems are organically united or combined.

The fact is that models which reproduce such a large number of parts with many different theoretical backgrounds are individually modeled for the identification according to the physical unit system in which the parts are included or the application thereof, with a mutual theoretical relationship being neglected regardless of high generality of the individual part and mechanism. For this reason, it has been disadvantageous that the above-mentioned two types of prior art based on the techniques of the mechanical system can be applied only to a specific phenomenon of mechanical system vibration.

Also, in the prior art, the model (part) has been identified only by one dimension "strength (flow quantity)" for two dimensional quantities "quantity (potential quantity)" and "strength" which prescribe energy. Namely, since both rules which govern each of the two kinds of quantities composing energy are not applied, continuity of velocity and acceleration has not been represented on the identified model, so that it was disadvantageously difficult to unite the parts with each other.

Furthermore, since the prior art only expresses a structure of a model, i.e. a positional relationship of the characteristics composing the model but not the functions of the characteristics, structural phenomena which the characteristics are compounded to reveal, e.g. a natural frequency, a natural mode shape, or a characteristic matrix of an entire structure can only be made clear by the identification, so that it has been impossible to directly clarify the characteristic values governing the function of an object.

It is accordingly an object of the present invention to provide a characteristic value identification method and an apparatus therefor which can develop models across different physical unit systems to be integrated into an entire model, similar to a product in which

2

individual parts are combined.

Disclosure of Invention

A basic process for identifying an internal characteristic value of 5 a functional model relating to a product and a part (hereinafter both simply referred to as a part) in the present invention is shown in Fig.1. This diagram illustrates an identification method taking advantage of the functional model being a modeling method including a steady characteristic value and a transient characteristic value.

10 First of all, the functional model modeled in a process 1 originally includes the steady characteristic value and the transient characteristic value. Accordingly, the functional model identification of the present invention according to claim 1, these internal characteristic values are separately carried out by a steady 15 identification process 2 and a transient identification process 3. Namely, for a basic process of the identification, the transient identification process 3 is executed after the steady identification process 2, since the steady characteristic value is free from interference of transient state and the transient state interferes with 20 the steady characteristic value.

The steady identification process 2 further includes the following processes according to claims 2-5. Firstly, in a process 21, a steady functional model is obtained which reproduces a function, performance, and characteristic of a steady state from the functional model of the 25 part. This steady functional model turns into a model including only a steady characteristic except a transient characteristic. In a process 22, a steady test of a part which forms an identification subject is performed to collect steady test data. In a process 23, the steady internal characteristic value is identified by using the test data to be 30 provided to the functional model by a process 24.

The transient identification process 3 includes the following

3

processes according to claims 6-9. Firstly in a process 31, a transient test model of a part which forms an identification subject is prepared, and the test is performed to collect transient test data. In a process 32, a transient internal characteristic value of the functional model is

5   identified by using the test data. As shown in a process 4, the steady internal characteristic value identified in the process 24 is reflected to the transient identification process 3.

Hereinafter, along these processes, the test model and the identification method for identifying the functional model will be

10   described taking a motor as an example enabling a brief description.

Firstly, the functional model of the process 1 common to each claim will be described by taking a DC (direct current) motor as an example.

<Modeling of motor>

15   (1) Basic function of motor

A basic function of a motor is that electric energy is inputted, and the energy is converted into a rotation energy to be outputted. As for the energy conversion at this time, a voltage V_M and a current I_M are applied to the electric system of the motor whereby an angular velocity

20   ω_M and a torque T_M are outputted from the rotation system. Also, a loss characteristic, an accumulation characteristic, and an additional load are included in the motor as an internal load, so that these determine a behavior and a loss characteristic of the motor.

A torque coefficient χ_T [Nm/A] expressed by the ratio of current

25   and torque, and a velocity coefficient χ_ω [V/(rad/sec)] expressed by the ratio of angular velocity and induced voltage are known between the electric system and the rotation system of the DC motor. An ideal motor model which directly converts an input/output state value with these coefficients being made a basic function can be expressed by the

30   following equation:

4

$$\left.\begin{array}{l} \chi_T = \dfrac{T_M}{I_M} = \dfrac{1}{2\pi}\dfrac{P}{a}Z\phi \times 10^{-8} \\[3mm] \chi_\omega \cong \dfrac{V_M}{\omega_M} = \dfrac{1}{2\pi}\dfrac{P}{a}Z\phi \times 10^{-8} \end{array}\right\} \qquad \cdots \text{Eq.(1)}$$

In equation (1), P is the number of poles in armature, "a" is the number of armature parallel circuits, Z is the number of all conductors, and ϕ is all of the magnetic flux per pole. They are characteristics

5   determined by a motor structure. Also, the magnetic flux ϕ is determined by the structure in a separately excited type motor which uses a permanent magnet for a field in the same way as above, and is influenced by a state value of the electric system in a self-excited motor having a field winding. Eq.(1) is a basic one common to a DC rotator

10   applied to a DC generator as well.

A torque coefficient χ_T and a velocity coefficient χ_ω of Eq.(1) performs a physical unit system transformation from current into torque, or from angular velocity into voltage in the same equation. Therefore, these coefficients will be hereafter called motor constants

15   expressed by M_M. As for the relationship between the motor constants and the internal load, the electric system and the rotation system are considered to be the motor internal load with the coefficients being bordered. A basic form of the motor model combining the relationship of the basic function of the motor constant M_M and the internal load is

20   shown in Fig.2.

In Fig.2, the input/output state value of the electric system is connected to a power supply, and the input/output state value of the mechanical system is united with an external machine load. Also, as for the flow of the state value, the lower flow represents a flow system

25   in which the current I_M of the power supply is converted by M_M into a flow of the output torque T_M which drives the external load, while the upper flow represents a potential system in which the angular velocity ω_M received from the external load is converted into the motor induced

5

voltage by M_M to turn into a flow of the voltage V_M returned to the power supply.

Thus, the mechanical system and the electric system are united by the strength of energy called a potential quantity and the quantity of energy called a flow quantity, thereby enabling energy rules of two dimensions, equilibrium of forces and the continuity of velocity, to be satisfied.

(2) Functional model of motor

An electric circuit diagram of the motor model is shown in Fig.3.

In the electric system of Fig.3, R_M is a winding resistance, L_M is an inductance, and R_C is an insulation resistance of the winding. Also, the rotation system has a moment of inertia J_M, a viscous resistance D_M, and a friction torque T_{MF}. The functional model expressing these relationships is shown in Figs.4(1) and 4(2). It is to be noted that such a functional model itself has already been disclosed in the Japanese Patent Application Laid-open No. 9-91334.

In Fig.4(1), the right side of the motor constant M_M forms the rotation system internal load, and the left side thereof forms the electric system internal load. This model has a voltage drop E_{MB} of a brush which supplies the current I_M to the armature, and a friction torque T_{MF} of the rotation system as the additional load. When the influence of both is neglected, T_{MF} and E_{MB} can be assumed to be 0. It is to be noted that x_M and x_L in Fig.4(1) are internal state values. Also, the following velocity correction coefficient δ_M is added to the motor constant M_M by taking into account the variation of the torque coefficient χ_T and the velocity coefficient χ_ω.

$$\left. \begin{aligned} \delta_M &= \frac{\chi_\omega}{\chi_T} \\ M_M &= \chi_T \end{aligned} \right\} \qquad \cdots \text{Eq.(2)}$$

A government equation of such a motor functional model in Fig.4(1) is given by the following equation:

$$\begin{bmatrix} 0 \\ 0 \\ \omega_M \\ V_M \end{bmatrix} = \begin{bmatrix} -J_M & 0 & -D_M & M_M & -1 & 0 & -T_{MP} \\ 0 & -L_M & -\delta_M M_M & -(R_M + R_c) & 0 & R_c & -E_{MB} \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_c & 0 & -R_c & 0 \end{bmatrix} * \begin{bmatrix} \dot{x}_M \\ \dot{x}_L \\ x_M \\ x_L \\ T_M \\ I_M \\ 1 \end{bmatrix} \quad \cdots \text{Eq.(3)}$$

In equation (3), the 1st-2nd rows form state equations, and the 2nd-4th rows form output equations.

It is to be noted that Eq.(3) can be derived from the following process shown in Fig.4(1);

· A white circle adds the inputted state values to make the output state value;

· At a black circle, the outputted state value is equal to the inputted state value;

· A characteristic expressed by a square makes the product of the input state value and the characteristic the output state value;

· A white circle with a mark ✕ outputs the product of the input state values or input signals;

· A while circle with a mark ─ makes the state value negative;

· A triangle integrates a differential quantity of the inputted state value to make the output state value;

· A large white circle on which a variable name is written expresses the state value generated in the functional model as an additional load.

(3) Uniting with motor power supply

A battery forming the power supply of the motor is modeled. Fig.5 shows a circuit diagram of the battery, and Fig.6 shows its functional model. In the battery of Fig.6, a voltage V_B and a current I_B are connected to the voltage V_M and the current I_M of the motor shown in Fig.4(1). Also, the characteristic of Fig.6 has E_0 as an induced electromotive force of the battery, and R_E as an internal resistance of the battery.

The government equation of the battery in Fig.5 is given as

7

follows:

$$[I_B] = \begin{bmatrix} -\dfrac{1}{R_B} & \dfrac{1}{R_B}E_0 \end{bmatrix} \begin{bmatrix} V_B \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.(4)}$$

Uniting the motor model and the battery model is given by the following equation by substituting equation (4) for Eq.(3).

$$\begin{bmatrix} 0 \\ 0 \\ \omega_M \\ V_M \\ I_M \end{bmatrix} = \begin{bmatrix} -J_M & 0 & -D_M & M_M & -1 & -T_{MF} \\ 0 & -L_M & -\delta_M M_M & -(R_M + R_C R_B Y_0) & 0 & R_C I_0 - E_{MB} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -R_B R_C Y_0 & 0 & R_C I_0 \\ 0 & 0 & 0 & R_C Y_0 & 0 & I_0 \end{bmatrix} \cdot \begin{bmatrix} \dot{x}_M \\ \dot{x}_L \\ x_M \\ x_L \\ T_M \\ 1 \end{bmatrix} \quad \cdots \text{Eq.(5)}$$

The 1st-2nd rows of equation (5) form the state equations, and the 3rd-5th rows form the output equations. An abstracted equivalent admittance Y_0 and a current source I_0 in Eq.(5) are expressed by the following equations:

$$Y_0 = \frac{1}{R_B + R_C} \qquad \cdots \text{Eq.(6)}$$

$$I_0 = Y_0 E_0 \qquad \cdots \text{Eq.(7)}$$

Thus, a characteristic value identification method according to the present invention uses a functional model of a part based on a potential quantity and a flow quantity representing energy applied to the part, comprises a first process for preparing that functional model, a second process for converting the functional model into a steady functional model in a steady state to identify a steady internal characteristic value, and a third process for identifying a transient internal characteristic value in a transient state of the functional model by using the steady internal characteristic value (claim 1).

Thus, in the characteristic value identification method of the present invention, the functional model of the part is prepared by the energy rules called the potential quantity and the flow quantity, and the transient identification is performed after the steady identification of its internal characteristic value, thereby enabling accurate identification of the characteristic values for all the parts and modeling

8

of an integrated product.

The above-mentioned second process may include a first step for determining an internal characteristic value of at least one steady test model from the steady functional model, a second step for collecting steady test data by performing a test corresponding to the steady test model, and a third step for identifying a steady internal characteristic value of the internal characteristic value based on the steady test data (claim 2).

The above-mentioned first step may determine the internal characteristic value from a government equation in the steady state of the functional model (claim 3).

Also, the above-mentioned third step may convert the government equation into a recurrence equation to determine the steady internal characteristic value from a recurrence coefficient of the recurrence equation (claim 4), and may divide the steady internal characteristic value into a known factor and an unknown factor to identify the steady internal characteristic value of the unknown factor (claim 5).

Furthermore, the above-mentioned third process may include a first step for determining an internal characteristic value of at least one transient test model in a transient state of the functional model, a second step for collecting transient test data by performing a test corresponding to the transient test model, a third step for applying the steady internal characteristic value to the internal characteristic value of the transient test model to generate transient phenomenon reproduction data, and a fourth step for correcting the transient phenomenon reproduction data based on an error between the transient phenomenon reproduction data and the transient test data, thereby identifying a transient internal characteristic value (claim 6).

When the error does not lie within an allowable range, the above-mentioned fourth step may repeatedly correct a predetermined

transient internal characteristic value within the transient phenomenon reproduction data until the error lies within the allowable range, and determine the transient internal characteristic value to be identified when the error lies within the allowable range (claim 7).

Also, the above-mentioned fourth step may preliminarily calculate a variance deviation, as a time history sensitivity, to an initial value at a time when each transient internal characteristic value is increased or decreased at a fixed ratio, and select a transient internal characteristic value having a maximum sensitivity within the time history sensitivity as the predetermined transient internal characteristic value (claim 8), or may select a transient internal characteristic value having the time history sensitivity similar to the error as the predetermined transient internal characteristic value (claim 9).

It is to be noted that the fourth step may simultaneously select a plurality of transient internal characteristic values having different maximum sensitivity times as the predetermined transient internal characteristic value (claim 10).

Also, a characteristic value identification apparatus according to the present invention comprises block replacement means for a functional model of a part, test reproduction means for reproducing at least one steady test model in a steady state of the functional model and at least one transient test model in a transient state, testing means of the part for performing a steady test and a transient test respectively corresponding to the steady test model and the transient test model, measurement means for collecting steady test data and transient test data at a time when a steady test and a transient test of the part are performed by the testing means, and calculating means for identifying a steady internal characteristic value of the steady test model by using the steady test data, for applying the steady internal

10

characteristic value to the transient test model to generate transient phenomenon reproduction data, and for correcting the transient phenomenon reproduction data based on an error between the transient phenomenon reproduction data and the transient test data, thereby identifying a transient internal characteristic value (claim 11).

Thus, it becomes possible to quickly identify the functional model of the same kind.

When the error does not lie within an allowable range, the above-mentioned calculating means may repeatedly correct a predetermined transient internal characteristic value within the transient phenomenon reproduction data until the error lies within the allowable range, and determine the transient internal characteristic value to be identified when the error lies within the allowable range (claim 12).

Also, the above-mentioned calculating means may preliminarily calculate a variance deviation, as a time history sensitivity, to an initial value at a time when each transient internal characteristic value is increased or decreased at a fixed ratio, and select a transient internal characteristic value having a maximum sensitivity within the time history sensitivity as the predetermined transient internal characteristic value (claim 13), or may select a transient internal characteristic value having the time history sensitivity similar to the error as the predetermined transient internal characteristic value (claim 14).

It is to be noted that the calculating means may simultaneously select a plurality of transient internal characteristic values having a different maximum sensitivity time as the predetermined transient internal characteristic value (claim 15).

Furthermore, a virtual testing system according to the present invention incorporates the functional model, as a virtual prototype, having an internal characteristic value identified by a characteristic

11

value identification apparatus claimed in claim 11 and comprises condition assigning means for assigning a driving operation condition and an environment condition to the characteristic value identification apparatus, observation means for observing reproduction data

5   obtained by the virtual prototype when the driving operation condition and the environment condition are assigned, and evaluation means for evaluating an observation result of the observation means (claim 16).

Namely, in the identification of the internal characteristic value by the present invention, an evaluation of a function, a performance,

10 and a characteristic of a part as well as a product in an actual machine test can be regarded as a virtual test performed on a computer, and the actual machine test performed in a development process of designing, prototyping, and testing in the prior art can be omitted, so that it becomes possible to shorten the period and to reduce the development

15 cost by the virtual test.

The above-mentioned virtual testing system may further comprise another measurement means for measuring actual machine test data at a time when the driving operation condition and the environment condition are provided to an actual machine which forms

20 a subject of the virtual prototype, and re-identification means of the virtual prototype, wherein the evaluation means may compare an output of the measurement unit and the observation result, and make the re-identification means re-identify the virtual prototype according to the comparison result (claim 17).

25 A fixed virtual prototype may be incorporated into a part of a drive system and a load system connected to the part as the above-mentioned virtual prototype, the testing means may perform a test corresponding to the fixed virtual prototype, and the evaluation means at this time may make the re-identification means perform a re-

30 identification according to the comparison result (claim 18).

12

Brief Description of Drawings

Fig.1 is a block diagram showing a basic concept of a characteristic value identification method and an apparatus therefor according to the present invention;

5   Fig.2 is a block diagrams showing a basic system of a motor model with a potential quantity and a flow quantity of energy being mutually related;

Fig.3 is a diagram showing a general electric circuit of a motor;

Fig.4 is a diagram respectively showing a functional model and

10   symbols of a motor used in a characteristic value identification method and an apparatus therefor according to the present invention;

Fig.5 is a diagram showing a general electric circuit of a battery;

Fig.6 is a diagram showing a functional model of a battery;

Fig.7 is a block diagram showing a process for preparing a steady

15   test model group from a motor steady functional model relating to a characteristic value identification method and an apparatus therefor according to the present invention;

Fig.8 is a diagram showing a steady functional model of a motor;

Fig.9 is a diagram showing a motor model at the time of a steady

20   load test;

Fig.10 is a diagram showing a motor model at the time of a load test;

Fig.11 is a diagram showing a motor model at the time of a lock test;

25   Fig.12 is a diagram showing a motor model at the time of a induced voltage test;

Fig.13 is a diagram showing a motor model at the time of a braking test;

Fig.14 is a block diagram showing an identification process of a

30   steady functional model from a steady test model group in a characteristic value identification method and an apparatus therefor

according to the present invention;

Fig.15 is a graph showing a motor characteristic of a steady state;

Fig.16 is a diagram showing an external shape of a motor;

Fig.17 is a graph showing a steady internal characteristic value

5 of a motor with an ordinate and an abscissa in Fig.15 being exchanged;

Fig.18 is a graph showing a steady internal characteristic value
of a motor;

Fig.19 is a block diagram showing a transient identification
process of a functional model in a characteristic value identification

10 method and an apparatus therefor according to the present invention;

Fig.20 is a diagram showing a structure of an electrically driven
arm mechanism;

Fig.21 is a diagram showing a model at the time of an actual load
transient test of a motor;

15 Fig.22 is a diagram showing a transient test model at the time
when a motor axis is fixed;

Fig.23 is a diagram showing a fixed torque transient test model of
a motor;

Fig.24 is a diagram showing a model at the time of an inertial

20 rotation test of a motor;

Fig.25 is a diagram showing a motor operation switch circuit;

Fig.26 is a diagram showing a functional model of a motor
operation switch;

Fig.27 is a diagram showing an electric circuit of a switching

25 method;

Fig.28 is a diagram showing a functional model of an electric
circuit of a switching method;

Fig.29 is a diagram showing an electric circuit of a fixed current
control;

30 Fig.30 is a diagram showing a functional model of a fixed current
control circuit;

14

Fig.31 is a graph showing a trial simulation result before performing a transient identification in a characteristic value identification method and an apparatus therefor according to the present invention;

Fig.32 is a flow chart illustrating an operation of a transient identification in a characteristic value identification method and an apparatus therefor according to the present invention;

Fig.33 is a graph respectively showing a sensitivity of a characteristic value in a characteristic value identification method and an apparatus therefor according to the present invention;

Fig.34 is a graph respectively showing a relationship between a current deviation and a characteristic value time history sensitivity in a characteristic value identification method and an apparatus therefor according to the present invention;

Fig.35 is a graph respectively showing a simulation result after performing an identification in a characteristic value identification method and an apparatus therefor according to the present invention;

Fig.36 is a graph respectively showing a simulation result of a start and a stop in a characteristic value identification method and an apparatus therefor according to the present invention;

Fig.37 is a graph respectively showing a simulation result of a regular/reversed rotation and brake in a characteristic value identification method and an apparatus therefor according to the present invention;

Fig.38 is a block diagram illustrating a characteristic value identification apparatus according to the present invention by taking a motor as an example;

Fig.39 is a block diagram showing a relationship between a product development and a model;

Fig.40 is a block diagram showing a concept of a virtual test according to the present invention;

Fig.41 is a diagram showing a model at the time when a virtual testing system according to the present invention is applied to a car;

Fig.42 is a block diagram showing an embodiment of a virtual testing system according to the present invention;

5   Fig.43 is a block diagram showing an example applying a virtual testing system according to the present invention to an actual machine test of a transmission;

Fig.44 is a model diagram showing a virtual testing system of a drive system, a transmission, and a load system; and

10   Fig.45 is a block diagram showing an example applying a virtual testing system according to the present invention to an actual machine test of a power train.

Description of Reference Numerals

1 motor model (block replacement structure)

15   2 test reproduction model

3 tested motor

4 drive circuit unit

5 load generator

6 electric load

20   8, 34 measurement unit

9 calculation unit

10 virtual test model

11 virtual prototype

12 test standard model

25   13 engine model (motor model)

14 body model (generator model)

21 drive model (battery operation model)

22 load model (load generator model)

23, 37, 40 observation model, observation system

30   24 characteristic value update model

25 model replacement unit

16

30 virtual test portion

31, 38, 39 drive operation model, operation system

32, 41 environment condition model, environment system

33 actual machine test portion

5   35 evaluation model

36 control system input/output unit

50 tested transmission

51 tested power train (P/T)

71 drive system control unit

10   72 load system control unit

Throughout the figures, like reference numerals indicate like or corresponding components.

Best Mode for Carrying Out the Invention

15   Hereinafter, an embodiment of a characteristic value (model) identification method and an apparatus according to the present invention schematically shown in Fig.1 will be described.

1. Functional model in steady state

In order to perform the steady identification process 2 shown in
20   Fig.1, the steady functional model conversion is required as shown in the process 21. In this steady functional model conversion, it is necessary as will be described hereafter to convert the functional model into the steady functional model for reproducing the steady state of the part, and to further convert the steady functional model
25   into the steady test model according to steady tests of the part (process 210).

Since the steady identification utilizes the steady test data, the steady test model can make the steady functional model of the identification subject accord with the tested object to which the actual
30   machine test is performed, by modeling the tested object according to the condition and the contents of the steady test for generating the test

data. Fig.7 shows a flow of a series of model conversions.

1. 1 Conversion from function model into steady functional model

Since there is no transient variation in a steady state of a motor, neither the inductance L_M nor the moment of inertia J_M shown in Fig. 4A influences the steady internal characteristic value. Also, since the insulation resistance R_C in Fig. 4A has an extremely large value, the influence to the motor current I_M can be neglected. From the above-mentioned points, the motor model in the steady state where L_M, J_M, R_C of Fig.4(1) are eliminated turns into a functional model shown in Fig.8.

The left side of Fig.8 shows a battery model of Fig.6 in which the operation switch of the electric system is omitted, and the right side thereof shows a motor model in a steady state. From Fig.8, the motor model in the steady state can be expressed by the following government equation:

$$
\begin{bmatrix} \omega_M \\ V_M \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{D_M} & \dfrac{M_M}{D_M} & -\dfrac{1}{D_M}T_{MF} \\ -\dfrac{M_M \delta_M}{D_M} & R_M + \dfrac{M_M{}^2 \delta_M}{D_M} & E_{MB} - \dfrac{M_M \delta_M}{D_M}T_{MF} \end{bmatrix} \begin{bmatrix} T_M \\ I_M \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.(8)}
$$

For another method of deriving the steady government equation, the government equation in the steady state obtained by eliminating L_M, J_M, R_C from the government Eq.(3) of the functional model in Fig.4(1) can be obtained by the following processes:

① The equation obtained by eliminating the differential state values of $\dot{x}_M$ and $\dot{x}_L$ from Eq.(3) with L_M and J_M being assumed to be 0 is given as follows:

$$
\begin{bmatrix} 0 \\ 0 \\ \omega_M \\ V_M \end{bmatrix} = \begin{bmatrix} -D_M & M_M & -1 & 0 & -T_{MF} \\ -\delta_M M_M & -(R_M + R_c) & 0 & R_C & -E_{MB} \\ 1 & 0 & 0 & 0 & 0 \\ 0 & R_C & 0 & -R_C & 0 \end{bmatrix} * \begin{bmatrix} x_M \\ x_L \\ T_M \\ I_M \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.(9)}
$$

② The equation obtained by eliminating the internal state values of x_M and x_L from equation (9) is given as follows:

18

$$\begin{bmatrix} \omega_M \\ V_M \end{bmatrix} = \begin{bmatrix} -\dfrac{R_M + R_c}{D} & \dfrac{R_C M_M}{D} & \dfrac{M_M E_{MB} - (R_M + R_c)T_{MF}}{D} \\ \dfrac{R_C \delta_M M_M}{D} & -\dfrac{R_C(D_M R_M + R_C \delta_M M_M{}^2)}{D} & \dfrac{R_C(\delta_M M_M T_{MF} - D_M E_{MB})}{D} \end{bmatrix} * \begin{bmatrix} T_M \\ I_M \\ 1 \end{bmatrix}$$

$$\cdots \text{Eq.(10)}$$

"D" in equation (10) is assumed to be the following equation:

$$D = D_M(R_M + R_c) + \delta_M M_M{}^2 \qquad\qquad \cdots \text{Eq.(11)}$$

5 ③ The equation obtained by eliminating the insulation resistance by making $R_C = \infty$ from Eq.(10) is given as follows:

$$\begin{bmatrix} \omega_M \\ V_M \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{D_M} & \dfrac{M_M}{D_M} & -\dfrac{1}{D_M}T_{MF} \\ \dfrac{\delta_M M_M}{D_M} & -R_M - \dfrac{\delta_M M_M{}^2}{D_M} & \dfrac{\delta_M M_M}{D_M}T_{MF} - E_{MB} \end{bmatrix} * \begin{bmatrix} T_M \\ I_M \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.(12)}$$

The government equation (12) in the steady state derived from the government Eq.(3) of the functional model is equal to the
10 government equation (8) derived from the functional model in the steady state in Fig.8.

Accordingly, there are two methods for obtaining the steady government equation reproducing the steady state of the part; one by converting the functional model reproducing the transient state of the
15 part into the steady functional model, and the other by deriving the steady government equation from the government equation of the functional model. This indicates that the functional model in the steady state can be reversely depicted from the derived steady government equation, and that there is a reversibility between the
20 steady functional model and the steady government equation.

1. 2 Conversion from steady functional model into test model

A steady state of an actuality by the steady functional model will be considered, and the test model will be examined. The test model in the steady state models the test of the actuality which provides a
25 specified condition to an input/output system of a tested object, from the steady functional model and its government equation. The steady internal characteristic value is identified by relating the test data

obtained when the specified condition is assigned to the tested object, with the government equation.

The relationship between the specified condition in which the steady internal characteristic value is assigned to the motor model and the test is as follows:

① In case a fixed torque is provided to the motor with the power supply being connected, the model reproduces the relationship between the load applied to the motor and the steady internal characteristic value, so that the relationship between the motor current, the angular acceleration, and the load torque can be observed (steady load test:Fig.9).

② The case where the input torque T_M is assumed to be 0 corresponds to a motor rotation in an idle state, so that an idle angular velocity and an idle current are observed (idle test:Fig.10).

③ The case where an output angular velocity ω_M is assumed to be 0 corresponds to a lock state or a state at a starting moment when the motor rotation is compulsorily stopped, so that a lock current and a lock torque can be observed (motor lock test:Fig.11).

④ In case the input current I_M is assumed to be 0 and the input torque T_M is provided, the model which reproduces a generator function of the motor is obtained, so that the induced voltage and the angular acceleration can be observed (induced voltage test:Fig.12).

⑤ In case a resistor is connected to the input/output state value of the electric system to provide a fixed torque, the model which reproduces a regenerative braking force of the motor can be obtained, so that the relationship between the motor current, the angular acceleration, and a braking torque can be observed (steady braking test:Fig.13).

These test models are different from each other depending on how to provide the specified conditions. However, in an actual modeling, the values of the steady characteristic such as a steady functional model or a steady load test model and the input state are

20

made 0 or an infinite value (large value within a range where the value does not influence a reproduction result), so that each test model can be equivalently realized. It is necessary to perform at least one of such steady tests.

5   In view of the above-mentioned description, the motor test model performed from the steady functional model in Fig.8 under the specified conditions, is given as follows:

1. 2. 1 Motor steady load test

Fig.9 shows a steady load test which observes the performance 10 and the characteristic by providing the load torque to the motor.

In Fig.9, the input torque T_M is provided as a drive torque by the additional load from the steady functional model in Fig.8, and the output angular velocity ω_M is represented as an observation quantity. Accordingly, the government Eq.(8) of the motor is transformed into 15 the following equation:

$$\begin{bmatrix} \omega_M \\ V_M \end{bmatrix} = \begin{bmatrix} \dfrac{M_M}{D_M} & -\dfrac{1}{D_M}(T_M + T_{MF}) \\ R_M + \dfrac{M_M{}^2 \delta_M}{D_M} & E_{MB} - \dfrac{M_M \delta_M}{D_M}(T_M + T_{MF}) \end{bmatrix} \begin{bmatrix} I_M \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.(13)}$$

The government equation of the steady load test obtained by mutually substituting the government Eq.(4) of the battery for equation (13) is given as follows:

$$20 \qquad \begin{bmatrix} \omega_M \\ V_M \\ I_M \end{bmatrix} = \begin{bmatrix} \dfrac{1}{D_M} \dfrac{M_M(E_0 - E_{MB}) - (R_B + R_M)(T_M + T_{MF})}{(R_B + R_M) + \dfrac{M_M{}^2 \delta_M}{D_M}} \\[4ex] \dfrac{\left(R_M + \dfrac{M_M{}^2 \delta_M}{D_M}\right)\dfrac{1}{R_B}E_0 + E_{MB} - \dfrac{M_M \delta_M}{D_M}(T_M + T_{MF})}{1 + \left(R_M + \dfrac{M_M{}^2 \delta_M}{D_M}\right)\dfrac{1}{R_B}} \\[4ex] \dfrac{E_0 - E_{MB} + \dfrac{M_M \delta_M}{D_M}(T_M + T_{MF})}{\left(R_B + R_M + \dfrac{M_M{}^2 \delta_M}{D_M}\right)} \end{bmatrix} \qquad \cdots \text{Eq.(14)}$$

21

Equation (14) is a government equation reproducing a rated load test of the motor, where all of the equations assume the output state value reproducing the state value of the steady state.

1. 2. 2 Motor idle test

In the motor idle state, the input torque T_M of the steady load test model in Fig.9 becomes 0. The idle test model where the input torque T_M is eliminated from Fig.9 can be shown by Fig.10.

The government equation of the motor in Fig.10 turns into the following equation obtained by eliminating the load torque T_M from the government Eq.(13) of the steady load test:

$$\begin{bmatrix} \omega_M \\ V_M \end{bmatrix} = \begin{bmatrix} \dfrac{M_M}{D_M} & -\dfrac{1}{D_M}T_{MF} \\ R_M + \dfrac{M_M{}^2\delta_M}{D_M} & E_{MB} - \dfrac{M_M\delta_M}{D_M}T_{MF} \end{bmatrix} \begin{bmatrix} I_M \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.}(15)$$

The government equation of the idle test obtained by mutually substituting the government Eq.(4) of the battery for equation (15) is given as follows:

$$\begin{bmatrix} \omega_M \\ V_M \\ I_M \end{bmatrix} = \begin{bmatrix} \dfrac{1}{D_M}\dfrac{M_M(E_0 - E_{MB}) - (R_B + R_M)T_{MF}}{(R_B + R_M) + \dfrac{M_M{}^2\delta_M}{D_M}} \\[4mm] \dfrac{\left(R_M + \dfrac{M_M{}^2\delta_M}{D_M}\right)\dfrac{1}{R_B}E_0 + E_{MB} - \dfrac{M_M\delta_M}{D_M}T_{MF}}{1 + \left(R_M + \dfrac{M_M{}^2\delta_M}{D_M}\right)\dfrac{1}{R_B}} \\[4mm] \dfrac{E_0 - E_{MB} + \dfrac{M_M\delta_M}{D_M}T_{MF}}{\left(R_B + R_M + \dfrac{M_M{}^2\delta_M}{D_M}\right)} \end{bmatrix} \qquad \cdots \text{Eq.}(16)$$

1. 2. 3 Motor lock test

At the starting moment of the motor, the angular velocity ω_M becomes 0, where it can be regarded as a motor lock state in which the motor rotation is compulsorily stopped. Accordingly, the functional model of the lock test reproducing the motor lock can be shown by

22

Fig.11 where the output angular velocity ω_M of the steady functional model in Fig.8 is supposed to be 0. It is to be noted that since a brush voltage drop E_{MB} generated in the stop state of the motor rotation does not generate a fixed voltage drop but only assumes a minute voltage drop by a brush resistance, it is neglected and omitted.

In Fig.11, each steady internal characteristic value relating to the output angular velocity ω_M is eliminated from the steady functional model in Fig.8, so that the input torque T_M is shown by the observation quantity of the lock torque. The government equation of Fig.11 is given as follows:

$$\begin{bmatrix} V_M \\ T_M \end{bmatrix} = \begin{bmatrix} R_M \\ M_M \end{bmatrix} [I_M] \qquad \cdots \text{Eq.(17)}$$

The government equation of the lock test obtained by substituting the government Eq.(4) of the battery for equation (17) to be integrated is given as follows:

$$\begin{bmatrix} V_M \\ T_M \\ I_M \end{bmatrix} = \begin{bmatrix} \dfrac{R_M}{R_B + R_M} E_0 \\ -\dfrac{E_0}{R_B + R_M} M_M \\ \dfrac{E_0}{R_B + R_M} \end{bmatrix} [1] \qquad \cdots \text{Eq.(18)}$$

1. 2. 4 Motor induced voltage test

Fig.12 shows a model of an induced voltage test which provides the torque to the motor to observe a counter electromotive force V_M induced by the armature and the angular velocity ω_M.

In Fig.12, the steady internal characteristic value relating to the input current I_M is eliminated from the steady functional model in Fig.8, so that the output angular velocity ω_M is shown by the observation quantity. The government equation of Fig.12 is given as follows:

23

$$\begin{bmatrix} \omega_M \\ V_M \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{D_M}(T_M + T_{MF}) \\ -\dfrac{M_M \delta_M}{D_M}(T_M + T_{MF}) \end{bmatrix} [1] \qquad \cdots \text{Eq.(19)}$$

<u>1. 2. 5 Motor steady braking test</u>

Fig.13 shows a steady model of a regenerative braking which provides the torque to the motor and reversely returns the counter
5 electromotive force V_M induced by the armature to the motor through a braking resistance R_L to provide a braking force.

In Fig.13, the battery is eliminated from the steady functional model in Fig.8, the braking resistance R_L is connected, and the input torque T_M of the motor is provided as a drive torque. In addition, the
10 output angular velocity ω_M is shown as the observation quantity. The government equation of the motor in Fig.13 is given as follows:

$$\begin{bmatrix} \omega_M \\ V_M \\ I_M \end{bmatrix} = \begin{bmatrix} -\dfrac{M_M E_{MB} + (R_L + R_M)(T_M + T_{MF})}{(R_L + R_M) + \dfrac{M_M^{\ 2}\delta_M}{D_M}} \dfrac{1}{D_M} \\[4em] \dfrac{E_{MB} - \dfrac{M_M \delta_M}{D_M}(T_M + T_{MF})}{(R_L + R_M) + \dfrac{M_M^{\ 2}\delta_M}{D_M}} R_L \\[4em] \dfrac{E_{MB} - \dfrac{M_M \delta_M}{D_M}(T_M + T_{MF})}{(R_L + R_M) + \dfrac{M_M^{\ 2}\delta_M}{D_M}} \end{bmatrix} [1] \qquad \cdots \text{Eq.(20)}$$

The above-mentioned test models can be equivalently modeled by setting the following values to the characteristic or the input state
15 value of the steady load test model shown in Fig.9:

① The idle test model becomes equivalent by rendering the input torque $T_M = 0$.

② The lock test model becomes equivalent by rendering a viscous damping coefficient and the brush voltage drop respectively $D_M = \infty$,
20 $E_{MB} = 0$.

③ The induced voltage test model becomes equivalent by rendering

24

the motor current and the brush voltage drop respectively $I_M=0$, $E_{MB}=0$.
④ The braking test model becomes equivalent by rendering the internal electromotive force of the battery $E_0=0$, and by rendering the internal resistance R_B the braking resistance R_L.

5 ## 2. Identification of steady state

Fig.14 shows an identification process 2 of the steady internal characteristic value included by the steady functional model having been described referring to Fig.1. Since the steady internal characteristic value known beforehand from a design value, the
10 characteristic value of a similar article, the measured value of the characteristic, and the like can be determined as a fixed value in the steady identification process (process 26), remaining unfixed values can be identified (process 27).

As for an analysis technique applied to this, the government
15 equation of the steady test model is converted into a statistical model such as a canonical correlation analysis or a multiple fold recurrence analysis (simple recurrence analysis), determines a deviated recurrence coefficient from the steady test data, and derives the steady internal characteristic value from the relationship between the
20 deviated recurrence coefficient and the government equation (process 28). Also, as for the steady characteristic formed by many factors, the factors are analyzed, and divided into factors of which quantification is possible and factors of which quantification is difficult by modeling the forming process of the steady internal characteristic value with a
25 theoretical equation, an experimental equation, and the like, thereby identifying the factors of which quantification is difficult (process 29).

2. 1 Test plan of steady identification

In the steady functional model shown in Fig.8, there are six kinds of the steady internal characteristic values M_M, R_M, D_M, δ_M, T_{MF}, and
30 E_{MB} which form the subject of the steady identification. In order to determine these steady internal characteristic values, it is necessary to

firstly clarify the function of the steady model in Fig.8 and the characteristic of the steady internal characteristic values, and to clarify the relationship with the test method.

2. 1. 1 Verification of known/measurable steady internal characteristic
value (process 26)

Firstly, known characteristic values and the characteristic values which can be solely measured are clarified in the steady internal characteristic values included in the steady functional model. Among the characteristic values which govern the steady state of a general product or part, there are a large number of characteristic values which can be clarified without performing the steady test such as a characteristic value clarified in the literature or the like, a characteristic value which can directly utilize the design value, and a characteristic value which can be directly measured. Accordingly, it is important to determine the characteristic values by a preliminary investigation or measurement in case of the steady identification.

Reviewing the motor used here, such characteristic values to be determined are a brush voltage drop E_{MB}, an insulation resistance R_C omitted at the time of modeling the steady functional model in Fig.8, a motor winding resistance R_M, and the like. These steady characteristics are given as follows:

① Since being a voltage drop due to a graphite brush, the brush voltage drop E_{MB} assumes constant regardless of the current I_M during the motor rotation, and assumes a minute DC resistance in the stop state. Accordingly, 0.7 [V] shown in the literature is applied during the motor rotation, and the direct current in the stop state can be neglected.

② The insulation resistance R_C assumes the value [MΩ] which does not influence the result.

③ The winding resistance R_M of the motor can be determined by the ohmmeter or by calculating the motor voltage and current in the motor

26

lock state shown in Fig.11.

2. 1. 2 Steady functional model and statistical model (process 28)

There is a multivariate analysis such as a multiple fold recurrence analysis and a simple recurrence analysis in the analysis technique frequently used for the product development. The recurrence equation of the multiple fold recurrence model applied thereto is given as follows:

$$y = b_0 + b_1 x_1 + b_2 x_2 \cdots b_n x_n + e_{rr} \qquad \cdots \text{Eq.(21)}$$

Applying the multiple fold recurrence equation shown in equation (21) to the steady functional model including a plurality of unknown steady internal characteristic values will be examined. As for the method of application, dependent variables and independent variables in the steady government Eq.(8) are made correspond to an objective variable "y" and predictor variables x_1-$x_{n,}$, to be determined from the steady test data.

Also, deviated recurrence coefficients b_0-b_n are values combining known and unknown steady internal characteristic values. Accordingly, unknown steady internal characteristic values can be derived by relating (associating) the deviated recurrence coefficients to (with) the steady internal characteristic values. In Eq.(21), e_{rr} is a residual. Also, when the multiple fold recurrence equation has a plurality of different objective variables, these are expressed by simultaneous equations so that the canonical correlation analysis is applied. As a matter of course, the test data obtained by a plurality of different test methods, the deviated recurrence coefficient, and the steady internal characteristic value of the recurrence model can be related to each other.

In the multiple fold recurrence analysis of the motor, the steady internal characteristic value can be clarified by the following process from the data of the steady load test shown in Fig.9:

Firstly, as for the multiple fold recurrence model, the following multiple fold recurrence equations can be derived from the government

27

Eq.(13) of the steady load test model in Fig.9:

$$T_M = -T_{MF} - D_M \omega_M + M_M I_M \qquad \cdots \text{Eq.(22)}$$

$$T_M = -\left(T_{MF} + \frac{D_M E_0 - D_M E_{MB}}{M_M \delta_M}\right) + \left(\frac{R_M D_M}{M_M \delta_M} + M_M\right)I_M \qquad \cdots \text{Eq.(23)}$$

It is to be noted that equation (22) corresponds to the 1st row of
5   Eq.(13), and equation (23) corresponds to the 2nd row of Eq.(13). Since
the internal resistance R_B of the battery is very small, and the internal
electromotive force E_0 of the battery and a motor output voltage V_M are
considered to be approximately equal, E_0 in Eq.(23) is substituted for
the dependent variable V_M (motor output voltage) of Eq.(13).

10   The recurrence equation with the torque T_M of these equations
being made an objective variable and the motor current I_M and the
angular velocity ω_M being made predictor variables is given as follows
(process 281), where the upper equation of the following equations (24)
forms a multiple fold recurrence equation with two predictor variables,
15   and the lower equation forms a simple recurrence equation with a
single predictor variable:

$$\left.\begin{array}{l} T_M = B_{10} + B_{11}I_M + B_{12}\omega_M \\ T_M = B_{20} + B_{21}I_M \end{array}\right\} \qquad \cdots \text{Eq.(24)}$$

Also, constants (intercepts) B_{10}, B_{20}, and deviated recurrence
coefficients B_{11}, B_{12}, B_{21} can be expressed by the following equations:

20

$$\left.\begin{array}{l} B_{10} = -T_{MF} \\ B_{11} = -D_M \\ B_{12} = M_M \\ B_{20} = -D_M \dfrac{E_0 - E_{MB}}{M_M \delta_M} - T_{MF} \\ B_{21} = M_M + \dfrac{R_M D_M}{M_M \delta_M} \end{array}\right\} \qquad \cdots \text{Eq.(25)}$$

The steady internal characteristic values derived from the
deviated recurrence coefficients shown in equations (25) are given as
follows (process 282):

Firstly, T_{MF}, D_M, M_M correspond to the respective deviated
25   recurrence coefficients from the upper four rows of Eqs. (25).

28

$$T_{MF} = -B_{10}$$
$$D_M = -B_{11}$$
$$M_M = B_{12}$$

$\cdots$Eq.(26)

Then, δ_M can be derived by substituting equation (26) for four rows of Eqs. (25) as follows:

$$\delta_M = \frac{B_{11}}{(B_{20} - B_{10})B_{12}}(E_0 - E_{MB})$$

$\cdots$Eq.(27)

5   It is to be noted that the induced voltage E_0 of the battery and the brush voltage drop E_{MB} in equation (27) are assumed to be known steady internal characteristic values.

Moreover, R_M can be derived from the following equation by substituting Eqs. (26) and (27) for five rows of Eqs. (25):

10
$$R_M = \frac{B_{12} - B_{21}}{B_{20} - B_{10}}(E_0 - E_{MB})$$

$\cdots$Eq.(28)

While in the above-mentioned example, all of the steady internal characteristic values have been determined from the government Eq.(8) by the recurrence analysis, in many cases of the actual steady identification, the steady internal characteristic values are derived by combining a plurality of test methods. For example, in the above-

15   mentioned example, as for the 3rd row of Eqs.(26) deriving the motor constant M_M and equation (28) determining the winding resistance R_M, both M_M and R_M can be determined from Eq.(17) of the lock test model and the test data as well.

20   ## 2. 1. 3 Factor analysis of steady characteristic (process 29)

The steady internal characteristic value of the steady functional model includes many internal factors forming this characteristic. Accordingly, it is necessary to clarify the factors composing each characteristic value by performing a factor analysis, and to formulate

25   the result. Also, it is necessary to divide the factors into known factors and unknown factors based on the result, and to perform a steady identification for clarifying an influence degree of the unknown or

29

uncertain factors by the model or the test data.

To the steady identification method, a sensitivity analysis or the like is effective by which the relationship between the variance of the government factor and the steady internal characteristic value is taken as a sensitivity. Particularly, in case the steady internal characteristic value has a non-linear characteristic influenced by another state value, the sensitivity analysis is important.

If the motor constant is considered, for example, P, "a", and Z are known values in Eq.(1) since they are design constants determined by the motor structure. However, it is difficult to determine all of the magnetic fluxes ϕ per pole since it is distributed in the gap between the field and the armature. Accordingly, to identify the motor constant means to identify the magnetic flux ϕ by the test data. All of the magnetic fluxes ϕ per pole determined from the identified motor constant M_M are given as follows:

$$\phi = M_M \frac{2\pi a}{PZ} \times 10^8 \qquad \cdots \text{Eq.(29)}$$

Moreover, as a brief example, the winding resistance R_M of the motor is given by the following equation determined by a line length "l", a sectional area "S", a specific resistance "ρ", and a temperature coefficient "α", being governed by a temperature "t":

$$R_M = \rho \frac{l}{S}(1+\alpha t) \qquad \cdots \text{Eq.(30)}$$

From equation (30), l, S, ρ, and α assume the design values determined by the structure and the stuff, while the temperature "t" is governed by the temperature of the test environment and the temperature rise by self-heating of the motor. Accordingly in the test for performing the identification, the temperature of the motor forms an important factor which governs the characteristic value. Also, upon the examination of the high temperature environment and low temperature environment, it is required to perform a temperature

30

correction, by Eq.(30), to R_M in the government Eq.(3) and the steady government equations of equation (8) and subsequent equations.

<u>2. 1. 4 Motor steady characteristic</u>

The steady internal characteristic value of the motor is
5   represented by a torque-current characteristic representing the relationship between the output torque T_M [Nm] and the motor current I_M [A], and by a torque-velocity characteristic representing the relationship with the angular velocity ω_M [rad/sec], based on the result measured in the above-mentioned steady load test (Fig.9).
10 Firstly, the torque-velocity characteristic can be expressed by the following equation obtained by substituting the motor current I_M of Eqs.(22) and (23), the latter itself representing the torque-current characteristic:

$$T_M = \left(\frac{M_M}{R_M D_M} (E_0 - E_{MB}) - T_{MF} \right) - \left(D_M + \frac{M_M{}^2 \delta_M}{R_M} \right) \omega_M \qquad \cdots \text{Eq.(31)}$$

15 If the torque-current characteristic and the torque-velocity characteristic of the motor are available from a catalog, technical materials, or the like, the steady internal characteristic value may be determined from the characteristic diagram. This motor characteristic is shown in Fig.15.

20 The relationship between the two recurrence lines in Fig.15 is expressed by Eq.(22). In Fig.15, the intersection of X axis and the torque-angular velocity characteristic shows the motor lock state, and the intersection of Y axis and the torque-angular velocity characteristic shows the idle state. Accordingly, as for the motor constant M_M and the
25 winding resistance R_M, their approximate values can be determined by substituting the motor current I_M, the torque T_M, and the voltage V_M in the lock state for Eq.(17). Also, by substituting the result for Eq.(22), an approximate value of the viscous resistance coefficient δ_M at the time of idling can be determined, whereas the friction torque T_{MF} is
30 neglected.

2. 2 Motor steady test and steady identification result

The characteristic value in the steady state is identified from the motor functional model shown in Fig.4(1). It is to be noted that the motor used in this identification is a small DC motor of a separately excited type widely used for an electric actuator of a car, and a permanent magnet is used for the field.

The steady test for the steady identification has been performed to the idle test, the lock test, and the steady load test. The idle test and the lock test have been performed as a test under the specified conditions of the motor. The former has been performed with the output axis of the motor being released in the state of the input torque $T_M=0$, and the latter has been performed with the output axis being fixed in the state of the output angular velocity $\omega_M=0$.

Moreover, in the steady load test, a string hung with a weight has been winded onto a drum attached to the motor output axis, whereby the load torque has been calculated from the mass of the weight and the radius of the drum. Also, the test conditions are shown in the following Table 3 together with the result of the steady identification.

Fig.17 shows a result of the steady test performed to the motor of Fig.16 and the recurrence equations, where X and Y axes of Fig.15 are exchanged.

Fig.17 is a diagram showing the measured values of the torque-current characteristic representing the relationship between the output torque T_M [Nm] in the steady state and the motor current I_M [A], and representing the relationship with the angular velocity ω_M [rad/sec], and its recurrence equation. The characteristic value on the X axis represents the motor idle state ($T_M=0$) as mentioned above, and the intersection between the torque-velocity characteristic and the Y axis shows the lock state or the starting moment of the motor with the angular velocity $\omega_M=0$. The points shown by variable names in Fig.17 show a basic characteristic and a rating characteristic (dotted line) in

32

Table 1. Also, the black circle in Fig.17 shows the measured values.

Moreover, the basic performance at the time of starting and idling obtained in Fig.17 is shown in Table 1, and a catalog specification published by a motor maker is shown in Table 2 as reference data.

5

TABLE 1

	CHARACTERISTIC NAME	SYMBOL	UNIT	CHARACTERISTIC VALUE
MOTOR	IDLE CURRENT	I_{M_0}	[A]	0.1
	IDLE ANGULAR VELOCITY	ω_{M_0}	[rad/sec]	1410.0
	STARTING TORQUE	T_{M_L}	[Nm]	28.0×10^{-3}
	STARTING CURRENT	I_{M_L}	[A]	4.0
TEST POWER SUPPLY	INTERNAL ELECTROMOTIVE FORCE	E_B	[V]	12.0
	POWER SUPPLY INTERNAL RESISTANCE	R_B	[A]	1.0×10^{-3}

TABLE 2

CHARACTERISTIC NAME	SYMBOL	UNIT	CHARACTERISTIC VALUE	CONDITION	
RATED CURRENT	I_{M_S}	[A]	0.57	MAX	0.9
RATED ANGULAR VELOCITY	ω_{M_S}	[rad/sec]	1210.0	TOLERANCE	± 160.0
RATED LOAD	T_{M_S}	[Nm]	4.0×10^{-3}		
RATED VOLTAGE	V_M	[V]	12.0		

Table 3 shows a result of the steady identification by the test data of Fig.17.

TABLE 3

	CHARACTERISTIC NAME	SYMBOL	UNIT	CHARACTERISTIC VALUE
MOTOR STATE CHARACTERISTIC	VISCOUS RESISTANCE COEFFICIENT	D_M	[Nm/(rad/sec)]	0.65×10^{-6}
	KINETIC FRICTION TORQUE	T_{MF}	[Nm]	0.1×10^{-6}
	WINDING RESISTANCE	R_M	[Ω]	3.0
	BRUSH VOLTAGE	E_{BR}	[V]	0.7
	INSULATION RESISTANCE	R_C	[MΩ]	10.0
	MOTOR CONSTANT	M_M	[Nm/A]	7.25×10^{-3}
VELOCITY COEFFICIENT CORRECTION		δ_M		1.0
TEST CONDITION (KNOWN)	TEST VOLTAGE	E_0	[V]	12.0
	INTERNAL RESISTANCE	R_B	[Ω]	50.0×10^{-3}
	AMBIENT TEMPERATURE	t_P	[deg]	25.0

10

Table 3 is a result assembled according to the process of the steady identification examined so far. Among the identified steady internal characteristic values, E_{BR} has been assumed to be a prescribed value determined from the literature. Also, R_C is a measurement result of the insulation testing set. The other steady internal characteristic values M_M, R_M, D_M, δ_M, and T_{MF} are determined from the multiple fold recurrence analysis and the simple recurrence analysis by the above-mentioned Eqs.(24)-(27). Also, since the internal resistance R_B of the battery is so small that the resistance value of the current measurement distributary unit has been applied to the internal resistance R_B of the battery.

It is to be noted that in order to determine five coefficients B_{10}, B_{20}, B_{11}, B_{12}, and B_{21}, five simultaneous equations are required. T_M, I_M, and ω_M are vectors where equal to or more than five values determined by the characteristic of Fig.17 exist.

Fig.18 shows a simulation result of the thus identified steady internal characteristic values by using the steady government equation obtained by substituting Eq.(4) of the battery model for Eq.(8) of the motor steady state.

Thick solid lines in Fig.18 show results of the steady state of the angular velocity ω_M and the motor current I_M, while thin dotted lines show simulation results performed in Eq.(5) by using the transient internal characteristic value before identification described later. It is seen from Fig.18 that the results of the steady state coincides with each other in the steady region where the transient state becomes stable.

3. Identification of transient state (process 32)

Since the steady internal characteristic values of the motor shown in the above-mentioned Table 3 are clarified, the moment of inertia J_M and the inductance L_M as transient internal characteristic values governing the transient function of the motor are identified next

34

with the measured value of the motor current I_M, by the transient identification process 32 shown in Fig.19.

As an identification method, approximate values are firstly provided to the transient internal characteristic values to perform a simulation so that initial values are determined (process 36), then the time history sensitivities of the transient internal characteristic values for the motor current I_M are determined (process 38), and the deviation (process 37) between the measured value (process 35) of the motor current I_M and the simulation value assumes the least for the sensitivity indexed.

Moreover, the viscous resistance coefficient δ_M and the kinetic friction torque F_{MF} already identified are again identified in the transient identification for the confirmation. As for the identification, the assembly/disassembly and the replacement by a block replacement method can be performed to the model of the operation system and the load connected to the motor source supply system and the rotation system.

3. 1 Conversion from functional model into transient test model (process 33)

The test model in the transient state reproduces an actuality test providing a specified condition to the input/output system of the tested object in the same way as the steady identification by the functional model and its government equation. In the transient identification, the test data obtained by providing the specified condition to the tested object, and the simulation result by the test model are related, so that the characteristic value group included in the government equation is identified. Also, the test model of the transient identification models the drive or the load to be incorporated by the following method:

① Input/output model for driving

The input/output model for driving is a model for supplying driving energy such as a power supply and a torque in order to drive

35

the tested object. This model occasionally has an operation system or a control system for operating the supplying method of the driving energy. For example, the system connected to the electric system of the motor corresponds to such a system including a battery of a power supply, an operation switch of a motor, a control unit, and the like. As a specific example, there is a braking resistance of the regenerative braking mentioned above, or the like.

② Input/output model for load

The input/output model for the load is a model for accumulating or consuming the energy such as a characteristic which forms the load of the tested object and an actual load. This model occasionally has the operation system or the control system for operating how to provide the load energy. In the rotation system or the mechanical system of the motor, there is a method for connecting a stiffness (spring stiffness), the moment of inertia, the viscous resistance coefficient, and the like.

It is to be noted that in case the characteristic whose value is large is connected, it can be considered that the output axis is fixed. Also, as an expediency for providing the fixed load, there is a method by which the current, the torque, and the like are provided as an additional load, and the voltage and the angular velocity which become a pair are made an observation quantity. For operating a machine load, the load is switched over by simultaneously using models of a clutch, a brake, and the like.

3. 1. 1 Actual load transient test model of motor (process 34)

In the transient test model which reproduces the state of the practical use, the battery model in Fig.6 is united with the electric system of the motor model in Fig.4(1), and an actual load model or an equivalent load model is further united with the rotation system to be converted into a model for an execution closed from the outside.

(1) Actual load model of electrically driven arm mechanism

Fig.20 shows a load model of an electrically driven arm

mechanism having an operation arm whose operation range is restricted by θ_{max} at a rack side of a worm gear, as an example of a practical load.

Fig.21 shows a functional model for an execution in which the
5 electrically driven arm mechanism in Fig.20 is incorporated in the battery and the motor model. The electrically driven arm mechanism in Fig.21 has a stiffness K_C of a stopper, a reduction ratio N_G of a reduction unit, and a contact radius L_C of the stopper. Inside the electrically driven arm mechanism, there are a presumed rotation
10 angle $\hat{\theta}_R$ of the arm and an internal state x_C.

Also, the condition judgment shown by a hexagon frame in Fig.21 is a model which judges an arm operation range, and operates a switch variable S_{WC}. This functional model has an additional load of torque T_L as an external load.

15 The government equations of the electrically driven arm mechanism are given as follows:

$$\left.\begin{array}{c}\begin{bmatrix}0\\T_M\\\omega_L\end{bmatrix}=\begin{bmatrix}-\dfrac{1}{K_CL_C{}^2S_{WC}}&0&N_G&0\\0&-N_G&0&-N_GT_L\\0&0&N_G&0\end{bmatrix}\begin{bmatrix}\dot{x}_C\\x_C\\\omega_M\\1\end{bmatrix}\\[4pt]\hat{\theta}_L=N_G\iint\dot{x}_M dt\end{array}\right\}\qquad\cdots\text{Eq.(32)}$$

In this government equations (32), the upper equation indicates the government equation of the electrically driven arm mechanism
20 shown on the right side of Fig.21, and the lower equation indicates the presumed rotation angle $\hat{\theta}_L$ of the arm. Also, the model determining the rotation range of the arm is given as follows:

$$if(\hat{\theta}_R \geq \theta_{max})\ then\ (S_{WC}=1)\ else\,(S_{WC}=0)\qquad\cdots\text{Eq.(33)}$$

Equation (33) is for a condition judgment S_{WS} in which $S_{WC}=0$
25 when the presumed rotation angle $\hat{\theta}_R$ of the arm lies within the rotation range θ_{max}, and otherwise $S_{WC}=1$.

If the above-mentioned Eq.(5) where the battery and motor are integrated, and the government Eq.(32) of the electrically driven

37

arm mechanism are integrated, the following equation can be obtained:

$$
\begin{bmatrix} 0 \\ 0 \\ 0 \\ \omega_L \\ \omega_M \\ V_P \\ I_M \\ T_M \end{bmatrix} =
\begin{bmatrix}
-J_M & 0 & 0 & -D_M & M_M & -N_G & -T_{MF}-N_G T_L \\
0 & -L_M & 0 & -\delta_M M_M & -R_M -R_C R_B Y_0 & 0 & R_C I_0 -E_{MB} \\
0 & 0 & -\dfrac{1}{K_C L_C{}^2 S_{WC}} & N_G & 0 & 0 & 0 \\
0 & 0 & 0 & N_G & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -R_C R_B Y_0 & 0 & R_C I_0 \\
0 & 0 & 0 & 0 & R_C Y_0 & 0 & I_0 \\
0 & 0 & 0 & 0 & 0 & N_G & N_G T_L
\end{bmatrix} *
\begin{bmatrix} \dot{x}_M \\ \dot{x}_L \\ \dot{x}_C \\ x_M \\ x_L \\ x_C \\ 1 \end{bmatrix}
$$

$$\cdots \text{Eq.(34)}$$

5   In equation (34), the 1st-3rd rows form the state equations, and the 4th and the following rows form output equations for observing the internal transient state value. It is to be noted that Y_0 and I_0 in the equations are an equivalent admittance and a current source respectively shown in equations (6) and (7).

10   (2) Axis fixed model of motor

The model in which the output axis of the motor is fixed can be shown by next Fig.22. This model can be replaced with the arm mechanism on the right side of the motor actual load transient test model in Fig.21.

15   Fig.22 is a model in which the model of the electrically driven arm mechanism in the actual load transient test model of Fig.21 is replaced with stiffness K_C which fixes the motor output axis. The motor torque T_{MF} in Fig.22 reproduces the lock torque in the state where the output axis of the motor is fixed. It is to be noted that the government

20   equation is omitted in this case.

3. 1.1.1 Fixed torque transient test model of motor

There is a fixed torque test for providing a fixed torque as a load in the load test performed in the actual machine test. This test model unites the battery model in Fig.6 with the motor model in Fig.4(1) to be

25   converted into the model for execution closed from the outside. The converted functional model for the execution is shown in Fig.23.

In Fig.23, by uniting the battery and the motor, the motor voltage V_M and the current I_M form the observation quantities. Moreover, since the input torque T_M of the motor becomes the load torque generated inside the model, the input torque T_M becomes the additional load T_M, and the output angular velocity ω_M becomes the observation quantity. It is to be noted that in the idle test of the motor, the additional load T_M can be made 0.

The government equation for execution of the function model therefor shown in Fig.23 is given as follows:

$$
\begin{bmatrix} \dot{x}_M \\ \dot{x}_L \\ \omega_M \\ V_M \\ I_M \end{bmatrix} = \begin{bmatrix} -\dfrac{D_M}{J_M} & \dfrac{M_M}{J_M} & -\dfrac{T_M + T_{MP}}{J_M} \\ -\dfrac{\delta_M M_M}{L_M} & -\dfrac{R_M + R_C R_B Y_0}{L_M} & \dfrac{R_C I_0 - E_{MB}}{L_M} \\ 1 & 0 & 0 \\ 0 & -R_C R_B Y_0 & R_C I_0 \\ 0 & R_C Y_0 S_{WA} & I_0 \end{bmatrix} * \begin{bmatrix} x_M \\ x_L \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.}(35)
$$

In equation (35), the 1st-2nd rows form the state equations, and the 3rd-5th rows form the output equations. It is to be noted that the equivalent admittance Y_0 and the current source I_0 are given by the above-mentioned Eqs.(6) and (7).

Moreover, the process by which Eq.(35) is derived from the above-mentioned Eq.(5) is as follows:

Firstly, the 1st and 2nd columns including the moment of inertia J_M and the inductance L_M are eliminated, and the dependent variables at the 1st and the 2nd rows are made $\dot{x}_M$ and $\dot{x}_L$. Then, the input torque T_M of the independent variable in Eq.(5) can be substituted for the additional load at the 1st row the 3rd column in Eq.(5).

3. 1. 1. 2 Inertia rotation test model of motor

With the motor, the motor voltage V_M, the current I_M, the angular velocity ω_M of the rotation system, and the torque T_M can be measured. Among them, the electric system particularly has a characteristic that data with high accuracy are easily measured. However in the functional model shown in Fig.23, the motor voltage V_M nearly equals

39

the electromotive force E_o of the battery, so that it can not be used as the data for identification.

However, as for the induced voltage V_M generated when the motor power supply is turned off, the test data for identification can be
5   measured by the inertial rotation test. The model of this inertial rotation test is shown in Fig.24.

Fig.24 shows a model of the inertial rotation test from the moment when the power supply of the motor in the idle state is turned off until the motor is stopped. It is to be noted that the insulation
10   resistance R_C is omitted because the current is minute. The motor model of the inertial rotation test shown in Fig.24 is given as follows:

$$
\begin{bmatrix} \dot{x}_M \\ \dot{x}_L \\ \omega_M \\ V_M \\ I_M \end{bmatrix} = \begin{bmatrix} -\dfrac{D_M}{J_M} & \dfrac{M_M}{J_M} & -\dfrac{T_{MP}}{J_M} \\ -\dfrac{\delta_M M_M}{L_M} & -\dfrac{R_M}{L_M} & -\dfrac{E_{MB}}{L_M} \\ 1 & 0 & 0 \\ -\delta_M M_M & -R_M & -E_{MB} \\ 0 & 1 & 0 \end{bmatrix} * \begin{bmatrix} x_M \\ x_L \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.(36)}
$$

In equation (36), the 1st-2nd rows form the state equations, and the 3rd-5th rows form the output equations. It is to be noted that the
15   transient test model of Fig.23 is used for the example of the transient internal characteristic value identification performed here, instead of the inertial rotation test model.

3. 1. 1. 3 Actual load transient test model of motor having operation system
20   (1) Operation switch

The start, the stop, the regular rotation, the reversed rotation of the motor, and the basic operation of the electric brake can be performed by a switch circuit shown in Fig.25. The test model in which the modeled switch circuit is incorporated into the actual load
25   transient test model of Fig.21 will now be examined.

The motor operation model can be incorporated between the voltage V_M and the current I_M which connect the battery and the motor

40

in the motor actual load transient test model shown in Fig.21. By incorporating the operation switch, the actual load transient test model in Fig.21 can reproduce the start, the stop, the regular rotation, the reversed rotation of the motor, and the drive state of the electric brake by the switch operation. It is to be noted that the simulation results of the model will be described after the identification of the transient state.

Fig.25 is a circuit diagram of the operation switch incorporated between the battery and the motor. The functional model of the switch circuit is shown in the next Fig.26.

The resistance R_L in Fig.26 is the braking resistance for the electric brake. Moreover, neither the contact resistance nor the insulation resistance of the switch are considered.

The operation switch in Fig.26 is composed of S_{WS} for starting and stopping the motor, S_{WL} for operating the regular/reversed rotation, and S_{WB} for selecting necessity/unnecessity of the electric brake. As for an operation signal for operating the switches, ON/OFF of the switches are respectively represented by "1" and "0". The functions of the switches are as follows:

① The switch S_{WS} supplies the power to the motor when $S_{WS}=1$, and stops the power supply when $S_{WS}=0$.

② As for S_{WL} which controls the regular/reversed rotation, a switchover switch variable S_{WL_0} assumes "1" when $S_{WL}=0$, so that the current I_M of the electric circuit in Fig.23 flows in the direction of the arrow to rotate the motor regularly. An S_{WL_1} assumes "1" when $S_{WL}=1$, so that the current flows reversely to rotate the motor reversely. Also, S_{WL_0} and S_{WL_1} are the switchover switch variables prohibiting that both of S_{WL_0} and S_{WL_1} simultaneously assume the state of "1" or "2". On the functional model, this operation makes S_{WL} on the current side switch over the polarity of the output current I_S, so that S_{WL} on the voltage side restores the input voltage V_S which has come back to the

original polarity.

③ As for the braking by the electric brake, the electric brake is made ON when $S_{WB}=1$ and OFF when $S_{WB}=0$ under the condition of the power supply being made OFF, i.e. $S_{WS}=0$. The electric brake consumes the induced current caused by the motor idling when the power supply is made OFF by the braking resistance R_L to generate the braking torque. This braking torque is determined by the braking resistance R_L, so that the maximum braking torque is generated when the resistance value is 0 [Ω].

The government equation determined from Fig.26 is given as follows:

$$\begin{bmatrix} I_M \\ V_B \end{bmatrix} = \begin{bmatrix} \dfrac{1}{R_L} S_{WB}(1-S_{wS}) & S_{WE} \\ -S_{WE} & 0 \end{bmatrix} \begin{bmatrix} V_M \\ I_B \end{bmatrix} \qquad \cdots \text{Eq.(37)}$$

S_{WE} of equation (37) is a power supply switch variable for switching over the motor start/stop, and regular/reverse direction of the current flow, which is expressed by the following equation:

$$S_{WE} = S_{WS}\left(S_{WL\_0} - S_{WL\_1}\right) \qquad \cdots \text{Eq.(38)}$$

The government equation of the power supply system obtained by mutually substituting the voltage V_B and the current I_B of the government equations of the battery and the operation switch in Eqs.(4) and (37) to be integrated is given as follows:

$$[I_M] = \begin{bmatrix} \dfrac{1}{R_B} S_{WA} & \dfrac{E_0}{R_B} S_{WE} \end{bmatrix} \begin{bmatrix} V_M \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.(39)}$$

S_{WA} in equation (39) is assumed to be a braking switch variable by which ON/OFF of the power supply and a necessity/unnecessity of the electric brake are selected, and is expressed by the following equation:

42

$$S_{WA} = S_{WE}{}^2 + \frac{R_B}{R_L} S_{WB} (1 - S_{WS})$$

$$OR$$

$$S_{WA} = S_{WS} + \frac{R_B}{R_L} S_{WB} (1 - S_{WS})$$

$\cdots$Eq.(40)

In equation (40), as for $S_{WE}{}^2$ in the upper equation, the switchover switch variable member of the regular/reversed rotation assumes $(S_{WL\_0}\text{-}S_{WL\_1})^2=1$, and $S_{WS}{}^2$ assumes either "0" or "1" from equation (38).

5 Therefore, the upper equation can be expressed by the lower equation arranged by $S_{WE}{}^2=S_{WS}$.

Finally, the government equation obtained by mutually substituting the motor model of the actual load transient test model in Eq.(32) and the voltage V_M and the current I_M of and the power supply

10 system in Eq.(39) to be integrated is expressed by the following equation:

$$
\begin{bmatrix} 0 \\ 0 \\ 0 \\ \omega_L \\ \omega_M \\ V_P \\ I_S \\ T_S \end{bmatrix}
=
\begin{bmatrix}
-J_M & 0 & 0 & -D_M & M_M & -N_G & -T_{MF}-N_G T_L \\
0 & -L_M & 0 & -\delta_M M_M & -(R_M + R_C R_B Y_0) & 0 & R_C I_0 - E_{MB} \\
0 & 0 & -\dfrac{1}{K_C L_C{}^2 S_{WC}} & N_G & 0 & 0 & 0 \\
0 & 0 & 0 & N_G & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -R_C R_B Y_0 & 0 & R_C I_0 \\
0 & 0 & 0 & 0 & R_C Y_0 S_{WA} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & N_G & N_G T_L
\end{bmatrix}
\bullet
\begin{bmatrix} \dot{x}_M \\ \dot{x}_L \\ \dot{x}_C \\ x_M \\ x_L \\ x_C \\ 1 \end{bmatrix}
$$

$\cdots$Eq.(41)

In equation (41), the 1st-3rd rows form the state equations, and

15 the 4th and after rows form the output equations. The abstracted equivalent admittance Y_0 and the current source I_0 in Eq.(41) are expressed by the following equations:

$$Y_0 = \frac{1}{R_B + R_C S_{WA}}$$

$\cdots$Eq.(42)

$$I_0 = Y_0 E_0 S_{WE}$$

$\cdots$Eq.(43)

20 As an applied example of operating the motor by the electronic circuit incorporated into a control unit or the like, it is possible to

43

incorporate the electronic circuit into the actual load transient test model in Fig.21 in the same way as the operation switch circuit of the motor in Fig.25.

Also, it is possible to replace the operation system of the motor including the above-mentioned switch mechanism by the block replacement method. It is to be noted that while there is another method by which the electronic circuit is incorporated by using high circuit technology, the minimum function necessary for driving the motor is modeled here. Accordingly, the non-linear characteristic of a semiconductor, the transient response of the electronic circuit and the like are excluded.

(2) Switching method

By the switching method, the ON/OFF ratio by which the electric power is supplied at a cycle which does not influence the motor speed is changed to perform a control. The switching method can be realized by periodically switching over S_{WS} in Fig.26. The electronic circuit diagram close to this method is shown in Fig.27 and its functional model is shown in Fig.28. Figs.27 and 28 respectively show a model including the battery.

In Fig.27, a signal voltage E_{CNT} of a rectangular wave applied from the outside is converted into a base current by a resistance R_A of a transistor T_R to make the transistor T_R perform an ON/OFF operation. At this time, E_0 and R_B respectively denote a battery voltage and an internal resistance. D_I in Fig.27 denotes a wheeling diode, and has the following two functions: One is a function of restoring the energy saved by the inductance of the motor winding generated when the transistor is turned OFF to the motor, and another is a function of guarding the transistor from the high voltage induced by the inductance. It is to be noted that a mechanism model of a switching signal generator is omitted.

In the switching operation of Fig.28, a conductive state of ON is

44

represented by a low resistance R_{ON} and an interrupted state of OFF is represented by a high resistance R_{OFF}, in which both are switched over. Also, the function of the wheeling diode is represented by a condition judgment S_{WD} shown by a hexagon frame and a resistance R_D of the conductive state. Namely, the condition judgment S_{WE} judges the voltage E_{CNT} of the signal generator with the detected voltage E_{TH}, the conductive resistance R_{ON} is selected when $S_{WE}=1$, and the interception resistance R_{OFF} is selected when $S_{WE}=0$. Selection is performed by the switchover switch variables S_{WE_1} and S_{WE_0}.

Moreover, as for the accumulated energy of the inductance, the release period is judged by the counter electromotive force of the inductance which has turned to be negative, so that the energy is restored to the motor through the conductive resistance R_D of the wheeling diode. The functions of the braking resistance R_L shown in Fig.26 and the resistance R_D in Fig.28 appear to be the same at a glance. However, the former functions by a positive induced voltage of the motor, while the latter functions by a negative counter electromotive force by the inductance. The government equation of the switching method taking these points into account is given as follows:

$$\begin{bmatrix} V_B \\ I_M \end{bmatrix} = \begin{bmatrix} R_{ON}S_{WE\_1} + R_{OFF}S_{WE\_0} & 1 \\ 1 & -R_D S_{WD} \end{bmatrix} \begin{bmatrix} I_B \\ V_M \end{bmatrix} \qquad \cdots \text{Eq.}(44)$$

It is to be noted that the switching signal generator is excluded.

(3) Fixed current control method

The electronic circuit for controlling the motor by continuously changing the motor current or voltage is as follows:

The basic function of the motor is to convert the given current into the drive torque by the torque coefficient x_T. Accordingly, when an electronic control is performed to the motor, it is a basic function of the fixed current control to freely set a current targeted and to maintain the current. Fig.29 shows one of control circuits for maintaining the output current I_S in proportion to the value of a designated current

45

I_{CNT}.

In Fig.29, a triangle shows an operational amplifier or the like which has a high amplification ratio inside. The current I_{CNT} targeted is converted into the voltage by the resistance R_S to be inputted to + side of the amplifier. Also, the controlled current I_M is converted into the voltage by the current detecting resistance R_E to be returned to − side of the amplifier, thereby performing a feedback control. It is to be noted that E_0 and R_B are respectively the induced voltage and the internal resistance of the battery.

Additional brief examination of the fixed current control will be described as follows:

The voltage applied to + and − sides of the amplifier are respectively $V_{A\_INP1}=R_S I_{CNT}$ and $V_{A\_INP2}=R_E I_M$, as seen from Fig.29. Also, assuming the amplification ratio of the amplifier is A_{MP}, the output voltage V_{A_OUT} is given as follows:

$$V_{A\_OUT} = (R_S I_{CNT} - R_E I_M)A_{MP}$$
$$= V_M + R_E I_M \qquad \cdots \text{Eq.(45)}$$

Also, the amplifier in Fig.29 has a high amplification ratio. Therefore, if equation (45) is arranged assuming $1/A_{MP}=0$, the equation of the output current I_M is given as follows, where R_S/R_E in the equation indicates the current amplification ratio:

$$I_M \cong \frac{R_S}{R_E} I_{CNT} \qquad \cdots \text{Eq.(46)}$$

V_{A_OUT} of Eq.(45) cannot generate the voltage equal to or more than a supply voltage V_B shown in Fig.29. Also, a voltage difference of an offset voltage V_{OFS} is necessary between an output voltage upper limit value of the amplifier and a power supply voltage. This relationship is expressed by the following inequality:

$$V_{A\_OUT} \le V_L - V_{OFS} \qquad \cdots \text{Eq.(47)}$$

The output voltage V_{A_OUT} of the inequality (47) restricts the upper limit value of the output current I_M, indicating the limit of the

fixed current control. The output current I_{SL} exceeding this limit is determined by the closed circuit of the voltage of the battery induced voltage E_0 and the offset voltage E_{OFS} shown in Fig.29, as well as the voltage drop by the motor winding resistance R_M, the current detecting

5 resistance R_E, and the battery internal resistance R_B. However, since E_0 is not included in the functional element of the fixed current control, it is necessary to replace E_0 with the supply voltage V_B which can be added to the functional element. The current I_{SL} considering this point is expressed by the following equation:

10
$$I_{SL} \cong \frac{V_B - E_{OFS}}{R_M + R_E} \qquad \cdots \text{Eq.(48)}$$

The current consumed by the internal circuit of the amplifier is very low. Therefore, by neglecting the current, equation (48) turns into the approximate equation of the current I_B supplied by the battery.

From the above-mentioned description, the fixed current control

15 circuit in Fig.29 has a function of switching over the controlled current I_M given in equation (46) to the uncontrolled current I_{SL} given in Eq.(48) to be supplied. The functional model of the fixed current control in which the above-mentioned contents are arranged and modeled can be shown in Fig.30.

20 Firstly, the government equation of the fixed current control can be obtained from Fig.30 as follows:

$$\begin{bmatrix} I_M \\ V_B \end{bmatrix} = \begin{bmatrix} 0 & S_{WAMP\_1} & \dfrac{R_S}{R_E} S_{WAMP\_0} I_{CNT} \\ 1 & R_E S_{WAMP\_1} & \dfrac{R_E R_S}{R_E} S_{WAMP\_0} I_{CNT} \end{bmatrix} \begin{bmatrix} V_M \\ I_B \\ 1 \end{bmatrix} \qquad \cdots \text{Eq.(49)}$$

In equation (49), S_{WAMP_1} and S_{WAMP_0} indicate switchover elements with the condition judgment for judging the limit of the fixed

25 current control.

Finally, as for the fixed current control provides an in-control while the current I_B within the control range of Eq.(46) is equal to or less than the current I_{SL} exceeding the control limit of Eq.(48), and a

47

non-control when the current I_B exceeds the current I_{SL}. This condition judgment S_{WAMP} provides the following equation. It is to be noted that $\hat{I}_B$ and I_{SL} in equation (50) are estimated state values.

$$if\ (\hat{I}_B < I_{SL})\ then\ S_{WAMP} = 1\ elkse\ S_{WAMP} = 0 \qquad \cdots Eq.(50)$$

5   In Eq.(50), $S_{WAMP}=1$ means that the condition is fulfilled so that the current is directly supplied from the battery, while $S_{WAMP}=0$ means that the condition is not fulfilled so that the fixed current control is performed.

3. 2 Determination of initial characteristic value

10   Characteristics which have not yet been clarified are mainly transient characteristic values inside the motor. In order to understand the relationship between the motor function and the functional model, the characteristic value is initialized by providing the design value shown in the following Table 4 or an initial

15   characteristic value obtained from a similar part, by applying a steplike voltage to the motor in the idle state, and by sequentially updating the characteristic value experimentally. It is a matter of course that the process and method performed here can be simulated by the computer.

TABLE 4

CHARACTERISTIC NAME	SYMBOL	UNIT	CHARACTERISTIC VALUE
INERTIA MOMENT	J_M	$[Nm/(rad/sec^2)]$	0.4×10^{-6}
INDUCTANCE	L_M	$[H]$	$3.0 \times 10{-}3$

20

Upon the identification, the simulation results at the time when the functional model, corresponding to model when $T_M = 0$ in Fig.23, in the idle state is initialized by providing the characteristic shown in the Table 4 to Eq.(35) are shown in Figs.31(1) and 31(2). It is to be noted

25   that for the steady internal characteristic value and the test condition except those shown in the Table 4, the above-mentioned identification

results of the steady state shown in the Table 3 are used. Also, since the additional load T_M is idle, it is made "0".

Fig.31(1) shows the motor current I_M [A] and the angular velocity ω_M [rad/sec]. In Fig.31(1), a thin dotted line indicates natural data of a measured current, a thick dotted line indicates a current I_{M_MEG} [A] where signal processing is performed to a measured result described later with a digital filter, a thick solid line indicates a current I_{M_SIM} [A] of the simulation result, and a thin solid line indicates an angular velocity ω_M [rad/sec] of the motor.

Also, in Fig.31(2), a thick solid line indicates a current deviation ΔI_{ERR} [A] of an initial value obtained by subtracting the current I_{M_MEG} after being signal-processed with the filter from the current I_{M_SIM} determined by the simulation, and a thin dotted line indicates a current deviation ΔI_{P_err} [A] at the time when a moment of inertia J_M described later is identified.

In Fig.31(2), the current I_M shows a rise immediately after the power supply is turned ON where a high starting current flows, and decreases with a lapse of time, being stabilized to the idle current. Oppositely, the angular velocity ω_M rises with a lapse of time to stabilize in the idle rotation number. The change of the motor current indicates that the induced voltage of the motor is governed by the angular velocity ω_M through the motor constant M_M.

3. 2. 1 Noise process of measured current

The motor current I_M is measured by connecting a distributary resistance R_S of 50 [mΩ] between the motor and the power supply. The starting current measured at this time is shown by a thin dotted line which varies extensively in Fig.31(1). The extensive variance indicated by the actually measured value is due to the brush and a commutator of the motor, and is remarkably shown in a low rotation region immediately after the start. Particularly, the extensive variance which occurs at the rise of the rotation depends on a rotation angle of the

49

commutator for the brush, which is remarkably shown in a small motor having a few contact pieces of commutator.

The result of performing the signal processing to the measured data with the digital filter in order to remove the extensive current variance is shown by the thick dotted line in Fig.31(1), for the filter characteristic, a low-pass filter with a cut-off frequency of 100 [Hz] is used. It is to be noted that since the phase delay of about 72 [msec] from the measured data has occurred due to filtering, the result of the signal processing in Fig.31(1) is made coincident with the measured data by forwarding the rising point by the phase difference. Thus, the diagonally rising component having moved before 0 [sec] shown in Fig.31(1) is neglected.

The identification processing is performed by using the data to which the filter processing is performed. However, it is expected that an error greatly influences the identification result since the current variance occurring at the start of the motor rotation is not completely excluded. Since this error is an uncertain variance dependent on a positional relationship between the brush and the commutator at the starting time described before, the identification is performed from this view point.

3. 2. 2 Time history sensitivity of characteristic (process 38)

It has been clarified that all of the characteristic values which form the subject of the identification are included in the motor current I_M obtained from the output state value of the output equation in the 5th row of Eq.(36). Therefore, in order to perform the identification, it is necessary to form a hypothesis by fully grasping the relationship between the characteristic values which form the subject and the motor current, and to verify it through the interpretation of the identification result. Accordingly, the followings are hypothesized for the influence of the characteristics on the motor.

① It is supposed that the moment of inertia J_M is proportional to the

change of the angular velocity (angle acceleration), provides strong influences during the acceleration when the change of the angular velocity is large, and does not provide influences in the steady state when the change is little.

5 ② It is supposed that the inductance L_M is proportional to the change of the motor current, provides influences when the current variance is large at the starting moment, and does not provide influences in the steady state when the current becomes stable.

③ It is supposed that the viscous resistance coefficient δ_M is 10 proportional to the angular velocity, provides influences as the load of the internal loss with the increase of the angular velocity, and assumes a fixed load in the steady state.

④ It is supposed that the kinetic friction torque F_{MF} is a constant and so is a characteristic not influenced by the state value change. The 15 motor has a structure of reducing the friction torque as much as possible, so that the influence is little.

It is seen from the above-mentioned contents that the respective ways in which the characteristic values contribute are different in the process of a time transition from the starting moment to the steady 20 state. Accordingly, if the sensitivity of the characteristic values for the change of the motor current I_M is supposed to be the index of the identification, it can be easily presumed that the identification is possible. It is to be noted that the above-mentioned ③ and ④ are added for examining the time history sensitivity of the steady internal 25 characteristic value.

The sensitivity of each characteristic value will be examined based on the above-mentioned result as follows (see flow chart in Fig.32):

It has been described that the simulation result in Fig.31(1) has 30 been performed at the initial values of the characteristic values, and the current deviation ΔI_{ERR} at that time is shown in Fig.31(2). In

51

order to make this the index of the identification, the influence which the characteristic value variance provides to the current deviation Δ I_{ERR} is clarified, so that the relationship between the characteristic value and the motor current can be grasped. This current deviation Δ

5   I_{ERR} can be expressed by the following equation (at step S3), with a current measured value I_{M_MEG} (at step S1 in Fig.33) and a simulation value I_{M_SIM} (at step S2) being made a deviation:

$$\Delta I_{ERR} = I_{M\_SIM} - I_{M\_MEG} \qquad \cdots \text{Eq.(51)}$$

If the deviation Δ I_{ERR} lies within an allowable range, the

10 transient identification is completed after verifying the identification result by the simulation described later (at steps S4 and S10).

From equation (51), the value of the simulation is high with respect to the measured value when the current deviation ΔI_{ERR} of Fig.31(2) is positive, and otherwise low. Moreover, an extensive violent

15 variance is included at the starting moment. Accordingly, in order to use the current deviation ΔI_{ERR} as a sensitivity of the motor current I_M for the characteristic change, it is required to remove the variance. Also, the offset quantity by the current deviation ΔI_{ERR} is included in the sensitivity.

20 A variance current deviation ΔI_{P_ERR} of the characteristic representing the sensitivity is expressed by the following equation to remove the variance portion of the deviation:

$$\left.\begin{aligned} \Delta I_{P\_err} &= I_{P\_SIM} - I_{M\_MEG} - \Delta I_{ERR} \\ &= I_{P\_SIM} - I_{M\_SIM} \end{aligned}\right\} \qquad \cdots \text{Eq.(52)}$$

On the upper term of equation (52), the I_{P_SIM} (at step S5)

25 indicates the simulation value at the time when the transient internal characteristic value is changed, and the initial value current deviation ΔI_{ERR} indicates the current deviation of the measured value I_{M_MEG} for the simulation value I_{M_SIM} of the initial value by Eq.(51).

From this equation, the variance current deviation ΔI_{P_ERR} of the

30 characteristic value can use the deviation of the simulation value I_{P_SIM}

of each characteristic value variance for the simulation value I_{M_SIM} of the initial value as a sensitivity as shown in the lower term of Eq.(52). However, since an identification accuracy is exceedingly evaluated by the initial value current deviation ΔI_{ERR}, it is necessary to proceed the identification while the ΔI_{ERR} is contained within an appropriate range at any time during the identification.

3. 2. 3 Identification method by time history sensitivity change

Firstly, the result (at step S6) upon having determined the current deviation ΔI_{P_ERR} at the time when the characteristic values are changed by +10 [%] and -10[%] with the time history is shown in Figs. 33B-33E. The four diagrams show the sensitivity seen with the time history at the time when the characteristic values are changed. Fig.33(1) is a diagram for comparing the sensitivities at the time indicated by thin dotted times in the lower four diagrams, so that the time history data are stored.

Also, in the respective current deviations of Fig.33(2)-33(5), J indicates the moment of inertia, L the inductance, D the viscous resistance coefficient, and F the kinetic friction torque, which are generally referred to "P (parameter)" as mentioned above. However, since the vertical axis scale in each diagram is the same as that in each diagram on the lower term, it is impossible to compare the four diagrams in parallel. Also, the solid line shows a result upon having increased the characteristic of the Table 4 by +10 [%], and the dotted line shows a result upon having decreased the same by -10 [%]. This calculation is performed to all of the characteristic values of the identification subject (at step S7).

It is seen that the characteristic becomes linear, since the result upon having changed the characteristic value by ± 10 [%] is symmetrical with respect to positive and negative in Fig.33(1). The moment of inertia J_M and the viscous resistance coefficient δ_M become directly proportional to the motor current, and the inductance L_M

53

becomes proportional to the motor current in which the positive and negative are inverted. These relationships almost agree to the above-mentioned hypothesis of the relationship between the motor current I_M and the characteristic, so that the variance of the deviation is removed.

5   The identification is performed with the current deviation Δ I_{P_ERR} at the time when the characteristic of Figs.33(1)-33(5) is changed being made a time history sensitivity. In the identification, trials are repeated so that the current deviation lies within an allowable range by the following process (at step S4):

10   Firstly, since the positive current deviation is large in the range of 0.02-0.06 [sec] from the initial value current deviation ΔI_{ERR} of Fig.31(2), the moment of inertia J_M in Fig.33(2) whose sensitivity is high in this region as shown in Fig.33(1) is selected (at step S8) to be reduced (at step S9) in the identification of the characteristic values.

15   Since a variance value DI_{ERR} at the starting moment comes near the upper side as shown in Fig.31(2), the inductance L_M of Fig.33(4) is increased.

As for the order of identifying these characteristic values, the above-mentioned steps S2-S9 are sequentially executed from the value having larger coefficient with the mutual relationship between the

20   initial value current deviation Δ I_{ERR} and each variance current deviation ΔI_{P_ERR} being made an index. Alternatively, when it is thought that the variances do not interfere with each other due to the time difference as shown in Figs.33(2) and 33(4), the identifications

25   may be simultaneously performed by the steps S2-S9.

It is to be noted that since the characteristic curve of the moment of inertia J_M is similar to the current deviation ΔI_{ERR} shown in Fig.31(2) in the curve of the time history change, only the moment of inertia J_M may be changed for the identification under the judgment

30   that the current deviation ΔI_{ERR} is most influenced by the moment of inertia J_M.

Among above-mentioned processes, the process firstly performed in which the updated value of the moment of inertia J_M is determined is shown in Figs.34(1) and 34(2).

Fig.34(1) is a diagram showing the current deviation ΔI_{ERR} in Fig.31(2) up to 0.06 [sec]. Point A in Fig.34(1) indicates a deviation quantity α which is desired to be reduced and the position (point of 0.03 [sec]). Fig.34(2) shows a sensitivity of the moment of inertia J_M at the point of 0.03 [sec] shown in Fig.33(1), in which the sensitivity point 0 (abscissa) is adjusted to the point A in Fig.34(1).

It is to be noted that the current deviation shown by the both ordinates is adjusted to the same scale. As for the deviation quantity α =0.2 [A] which is desired to be removed from Fig.34(1), it is seen from Fig.34(2) that the sensitivity becomes negative.

Accordingly, a correction ratio β =16.8 [%] of moment of inertia J_M is determined from an intersection B between the abscissa of the deviation 0 in Fig.34(1) and the extension of the negative sensitivity in Fig.34(2). From the Table 4, the updated moment of inertia J_M assumes $0.4 \times 10^{-6} \times (1\text{-}0.168) = 0.3328 \times 10^{-6}$.

The result upon having updated the moment of inertia J_M is a thin dotted line showing the variance current deviation ΔI_{P_ERR} of Fig.31(2). The above-mentioned process is expressed by the following equations (at step S9):

$$\left. \begin{array}{l} \beta = \dfrac{\alpha(t)}{\lambda(t)} \\[2mm] P_{M\_NEW} = P_{M\_OLD}(1 - \dfrac{\beta}{100}) \end{array} \right\} \qquad \cdots \text{Eq.(53)}$$

In equations (53), the upper term is an equation of the correction ratio β of the characteristic value, and the lower term is an equation of the characteristic value after the update. As for the variables in Eqs.(53), α (t) [A] is a current deviation quantity of the initial value current deviation ΔI_{ERR} at a time "t", λ (t) [A/%] is a sensitivity of a characteristic value at a time "t" similarly, P_{M_NEW} is a characteristic

value after the update, and P_{M_OLD} is a characteristic value before the update.

When the motor current and the characteristic value have a non-linear characteristic (time history sensitivity becomes asymmetrical) which are not proportional to each other, and the change range of the characteristic value greatly exceeds ± 10 [%], it is necessary to again determine the sensitivity from Eq.(52) to repeat the identification.

3. 3 Result of transient identification and simulation (at step S10)

(1) Identification result and simulation thereof

The characteristic values via the above-mentioned process of the transient identification are shown in Table 5. As test data for identification, a result of an idle test is used in which the setting torque of the fixed torque transient test is assumed to be 0.

TABLE 5

CHARACTERISTIC NAME	SYMBOL	UNIT	CHARACTERISTIC VALUE
INERTIA MOMENT	J_M	[Nm/(rad/sec^2)]	0.335×10^{-6}
INDUCTANCE	L_M	[H]	4.2×10–3

The simulation result in which the transient identification result is reflected is shown in Fig.35. The simulation has been performed by providing the transient identification result of the Table 5 and the characteristic value of the steady identification result of the Table 3 to the government Eq.(35) for execution of the fixed torque transient test model shown in Fig.23.

In Fig.35(1), the result out of consideration of the inductance L_M is added by a thin dotted line and the natural data of the motor current are omitted, while the others are the same as Fig.31. It is to be noted that the simulation out of consideration of the inductance L_M has been performed by the same Eq.(35) with $L_M = 10^{-12}$ [H] being made a minute value without influence.

When both are compared, it is seen that by the influence of the

inductance L_M the starting current which steeply rises at the starting moment is saved as an energy to be released with the decrease of the current.

As a result, the rising of the motor current and the peak value are
5 suppressed in a solid line (L_M>0) with respect to the thin dotted line ($L_M \fallingdotseq 0$), and the falling part shifts to the right side. Also, the identification results are almost coincident as shown by the current deviation ΔI_{ERR} of Fig.35(2), while the variance at the starting moment appears as it is in the form of the current deviation as mentioned
10 before.

(2) Simulation of actual load transient test model of motor

Since this identified motor model becomes a virtual prototype which accurately reproduces a motor unit, a model of a virtual test which reproduces the driving state of the actual machine can be made
15 by incorporating the functional model for operation in Fig.26 into the actual load transient test model shown in Fig.21 (see Fig.42 described later). The simulation result will be described:

The simulation is performed by providing the characteristic value of the electrically driven arm of the following Table 6 to Eq.(41).

TABLE 6

CHARACTERISTIC NAME	SYMBOL	UNIT	CHARACTERISTIC VALUE
DECELERATION RATIO	N_g		1/200
OPERATING ANGLE	θ_s	[rad]	1.57
STOPPER STIFFNESS	K_s	[N/m]	7.0×10^4
STOPPER RADIUS	L_s	[m]	0.04

20

It is to be noted that the characteristic values other than those in the Table 6 are the same as those of the motor model after the identification. Also, the motor operation is performed by the power supply switch S_{WS}, the regular/reversed rotation switch S_{WL}, and the
25 braking switch S_{WB} shown in Fig.26.

Firstly, the simulation result of the motor start and stop is given as follows:

The power supply switch S_{WS} is turned ON to start the motor with the regular/reversed rotation switch S_{WL} being made OFF and the braking switch S_{WB} being made OFF. Then, the load of 2 [N·m] is provided after 120 [msec], and the power supply switch S_{WS} is turned OFF after 280 [msec] with the load being provided. The simulation result is shown in Figs.36(1)-36(4).

Figs.36(1)-36(4) sequentially show a motor current I_M [A], a load torque T_L [Nm], a motor voltage V_M [V], a motor angular velocity ω_M [rad/sec], and an operation angle of arm θ_R [deg]. The motor current I_M increases, and the angular velocity ω_M decreases from the moment the load is added. At this time, the change of the operation angle θ_R becomes rather slow.

Also, when the power supply is OFF, the motor current I_M assumes 0 [A], the angular velocity ω_M decreases, and the load drives the motor from about 310 [msec], so that the reversed rotation occurs. Also, as for the motor voltage V_M after the power supply is turned OFF, the inductance L_M generates a spike-like voltage at the moment the power supply is OFF, and then the induced voltage V_W by the angular velocity ω_M of the motor occurs, so that the state where the motor is changed into the generator is described.

The simulation result of the motor regular/reversed rotation, as well as the braking is as follows:

Figs.37(1)-37(4) show an example in which the motor is stopped with and without the electric brake by OFF/ON of the braking switch S_{WB}. Figs.37(1)-37(4) show states as follows: The motor is started with the regular/reversed rotation switch S_{WL} being made OFF and the power supply switch S_{WS} being made ON to be compulsorily stopped with the stopper. Then, the motor is rotated reversely in 0.6 [sec] after the regular/reversed switch S_{WL} being made ON and is again

compulsorily stopped with the stopper on the opposite side. After the lapse of 1.4 [sec], the power supply switch S_{WS} is made OFF, so that the motor is stopped.

Figs.37(1)-37(4) sequentially show a motor current I_M [A], an operation angle of arm θ_R [deg], a motor angular velocity ω_M [rad/sec], and a motor torque T_M [Nm]. Also, the solid line of Figs.37(1)-37(4) shows the state where the electric brake by the braking resistance of R_L=1 [mΩ] is applied, while the dotted line shows the state without the brake. Both of the regular and reversed rotations generate an attenuated oscillation at the time of collision at the stopper.

Also, when the motor is compulsorily stopped by the stopper, a flexible structure of a stopper gum absorbs the maximum torque of the motor to be compressed. If the power supply is cut off in this state, the arm is pushed back by the compression power owing to the bend of the stopper. The effect of the electric brake appears at the stop state after 1.4 [sec]. It is seen from the motor angular velocity ω_M and the operation angle of arm θ_R that the motor idle by the stopper counterforce is well absorbed as shown by the solid line.

4. Motor identification apparatus

Hereinafter, an apparatus required for identifying the above-mentioned test model of the steady and transient states of the functional parts will be described.

The functional parts incorporated into the products have a structure working with assembling the functional parts to the input/output portion and by mutually associating them. As shown in Fig.21, the battery for driving, the electrically driven arm forming a load and the like are necessary e.g. for the motor test. Also, in order to control the motor, the operation system shown in Figs.25, 27, and 29 is necessary.

The test model for thus performing an identification by using the test data of the actual machine requires modeling the functional parts

59

which form the driving source and the load of the tested object. Subject to the influence by other functional parts in this way, it is possible to standardize the function and the behavior as the specification of the tested object and the test standard. If there is something which operates and reproduces the behavior just as standardized function and behavior, it can be used as a substitute common to each test method.

If the functional model which forms the substitute of the driving source and the load is modeled and incorporated into the test model as an identified model, the identification defined to the internal characteristic value of the tested object can be performed. Also, as for the testing unit and the test model, the group of the tested objects whose parts specifications are different can be replaced with block replacement means.

Fig.38 shows an example in which the concepts are applied to the motor identification apparatus. In the identification apparatus of Fig.38, a motor model 1 has a block replacement structure for a test reproduction model 22. A reproduction model 2 is composed of a drive model 21 such as a battery and an operation model, a load model 22 such as a load generator model, an observation model 23 for observing the state value of the motor model 1, and a characteristic update model 24 for updating the internal characteristic value.

Also, a drive circuit unit 4 takes charge of the battery and the operation system which forms driving source of a tested motor 3. A load generator 5 and an electric load 6 take charge of the mechanical load of the motor 3. The driving source and the mechanical load are modeled as a drive model 21 and a load model 22 already identified.

Furthermore, as for the relationship between the actual machine testing unit and the models, the former drive model 21 has a structure of controlling the drive circuit unit 4 through a drive system control unit 71, and the latter load model 22 has a structure of controlling the

60

load generator 5 through a load system control unit 72.

The measured value of the motor 3 is obtained at a measurement unit 8 to be provided to a calculation unit 9. The calculation unit 9 receives the observation value of the observation model 23 and the measurement from the measurement unit 8 to update a characteristic update model 24.

The motor drive model 21 shown in Fig.38 corresponds to the model in which the battery on the left side of Fig.21 and the operation system circuit of Figs.26, 28, and 30 are united. The load generator model 22 corresponds to the arm mechanism on the right side of Fig.21 and the fixed torque generation model of Fig.23.

The operation and the behavior reproduced on the former model are reproduced at the drive circuit unit 4 by the drive system control unit 71 to be provided to the motor 3 of the tested object. Similarly, the load state provided to the motor 3 is reproduced on the load generator 5 by the load system control unit 72 controlling the electric load 6.

Accordingly, if the motor functional model 1 shown in Fig.4(1) is connected to the reproduction model 2, the drive model 21 and the load model 22 preliminarily provided corresponding to the drive system and the load system turns into predetermined steady test models and control the drive circuit unit 4 and the electric load 6.

Together with this operation, the steady test data generated by the motor 3 is measured by the measurement unit 8, so that the calculation unit 9 which has received the data provides the government equation of the steady functional model i.e. the steady internal characteristic value to the motor model 1. Thus, the steady identification is completed.

Then, the reproduction model 2 changes the drive model 21 and the load model 22 into the transient test model for the transient identification. Together with this operation, the transient test is executed, so that the transient test data are provided to the calculation

unit 9 from the measurement unit 8. The calculation unit 9 compares the value obtained by substituting the already calculated steady internal characteristic value for the internal characteristic value inputted from the observation model 23 with the measured data from

5   the measurement unit 8. The internal characteristic value of the motor model 1 is properly updated as mentioned above, by the characteristic update model 24 so that an error between them becomes small to lie within an allowable range. Thus, the transient identification ends, so that all of the identification works are completed.

10   5. Virtual test

The model which reproduces the function, the performance, and the characteristic value of the parts or the products composed of the parts is identified with the test data of the actuality, so that the internal characteristic value and the reproductivity are verified.

15   Therefore, it can be utilized as a virtual prototype for performing various evaluation tests on the computer instead of the actual machine. An example where the virtual prototype is applied to the product development will be described.

5. 1 Relationship between product development and modeling

20   The development process of product and the formation process of model are shown by the relationship in Fig.39.

Fig.39 shows a relationship between a development process of a project stage, a design stage, a prototype and test stage, and modeling and identification performed in parallel with the development. Fig.39

25   shows a process including a concept of concurrent engineering in which development processes of the product are performed in parallel.

On the other hand, the process of modeling has a flow as follows: An abstract product target at the project stage is firstly modeled, the model is sequentially detailed along with the development process, a

30   validity of the project and design contents by the model is verified, and the identification is finally performed with the test data of the

62

prototype, so that the virtual test is performed executing computer simulation with the identification model instead of the various evaluation tests.

(1) Relationship between product development and modeling

5   If this virtual test is applied to the development of the car, for example, the process is given as follows:

As for the abstract model at the project stage such as a model reproducing a car performance which forms the target characteristics of the projected car such as an acceleration time of 0-400 [m], a

10   stationary fuel cost performance, and an acceleration performance, a possibility of achieving the target characteristics is verified by the model assembled with the characteristics such as a weight, a resistance, a power characteristic, and a gear ratio.

In the next product part formation and basic design, the model is

15   disassembled following the formation method of the basic functional parts such as an engine, a transmission, a body realizing the target characteristics, and modeling is performed with the internal characteristic values of the functional parts being clarified, so that the function and the performance required for the functional parts, and the

20   possibility of realizing the target characteristic value are verified.

Similarly, in the detailed design, the modeling is detailed according to the contents of the detailed design of an engine, a clutch, a brake, a transmission, a control unit, and the like, whereby the validity of the design contents in the details such as a torque variance, a

25   transmission shock, a vibration noise, and the control algorithm is verified with the model.

The model made by the above-mentioned process is sequentially disassembled into the lower model from the abstract model at the project stage along the part formation, so that a systematic model

30   hierarchized from the product to the part and its details is formed.

Also, in the above-mentioned process of the project, design and

modeling, the development is proceeded by the design drawing of the actuality realizing the target characteristic, and the model verifying the design drawing. However, both are eventually hypotheses. Accordingly, it is necessary to test both by an experimental car made

5   based on the design drawing or the like, to identify the model, and to verify the validity of the hypotheses.

(2) Relationship between product development and identification

By the above-mentioned reason, the identification shown in the lower side of Fig.39 is performed based on the data of the functional

10   parts and a car test. The identification and the test necessary therefor are performed separately in the above-mentioned steady and transient states. The model is converted in accordance with the test method as shown in Figs.9-13 for the steady test, and in Figs.21-30 for the transient test, so that the identification of the test model is performed

15   by the test data. In the identification performed here, the identification result of the test models firstly performed per functional part are integrated along the part formation to be made the identification of the product model.

It is supposed that the functional parts of the battery, the motor,

20   and the electrically driven arm in Fig.21 are individually modeled, for example, and the product in which the parts are mutually connected is an electric actuator. The model of the electric actuator can be represented by a hierarchized model where the models of the battery, the motor, and the electrically driven arm are made lower level. Also, it

25   is seen that the equation in which the models are integrated turns into Eq.(34).

Accordingly, if the motor at the center of Fig.21 and the electrically driven arm on the right side of Fig.21 are individually identified, and they are made the characteristic value of Fig.21, the

30   electric actuator on the upper hierarchy is naturally identified. The model which can faithfully reproduce the characteristic value and the

64

performance of the product along the mode of the actuality is called a "virtual prototype".

As an applying method of this hierarchized model, it is possible to convert the electric actuator model into the test model when the
5   battery and the electrically driven arm are already identified in Fig.21, to make the identified internal characteristic values fixed values, and to perform a partial identification defined to an unfixed internal characteristic value of the motor model.

5. 2 Virtual test by virtual prototype

10   Thus identified part model is confirmed as a virtual prototype of the part reproducing the function and the performance held by each part. Similarly, the product model in which the part models already identified are mutually connected and integrated means that the model is confirmed as a virtual prototype reproducing the product. Also,
15   these models result in the identification by converting the models into test models in accordance with the above-mentioned test methods, comparing and evaluating the reproducibility and the test result of the actuality, and verifying the difference between both.

Accordingly, the virtual prototype of the identified product and
20   parts can be evaluated as to the validity by performing the computer simulation instead of the various tests of experimental articles and the like. Performing the evaluation test of the actuality on the computer by utilizing the virtual prototype is called a "virtual test" of the parts or the product. The simulation which has verified the validity of the
25   identification result obtained in Figs.37-38 is also one example.

(1) Internal formation of virtual test model

The virtual test is usually applied with the test standard determining the same environment condition as the evaluation test of the actuality, a test condition and performance such as driving
30   operation, and an evaluation standard such as a success/failure judgment, a performance prediction, a presence/absence of abnormal

65

phenomena, and the like by the reproduction data of the performance and the behavior. This can be typically shown in Fig.40.

Fig.40 is a basic arrangement of a virtual test model 10 where a virtual prototype 11 and a test standard group 12 applied thereto are modeled to be incorporated. The virtual prototype in this arrangement comprises two kinds of functional part models, an already identified functional part model and a functional part model in which design values and characteristic values of similar parts are provided upon the virtual test.

Both are distinctive in that the former is used as a model of a part having a basic function governing the function and the performance of the product, while the latter is used as a model extended for various products whose characteristic values are different in the application, the structure, and the shape of the products. The product model having both models united indicates that the evaluation test of various products and the test evaluation of various product groups where the derived functional models (latter) of different characteristic values are combined with the identified basic functional model (former) can be performed by the virtual test.

(2) Virtual prototype example of virtual testing car

For example, a simple model of the virtual prototype for car in Fig.40 can be shown in Fig.41. Fig.41 is an example of a virtual prototype showing a functional model where the functional parts of the engine and the transmission are modeled to be integrated as a power train (P/T), and a functional model where various types of cars which are different in a structure and the like are modeled as a body, and both are integrated as a car. Between the models of the functional parts, the engine and the transmission are related with the angular velocity ω_e that is a potential quantity, and with the torque T_e that is a flow quantity, while the transmission and the body are related with the torque v_b that is a potential quantity, and with the torque f_b that is

a flow quantity.

The characteristics in the models are as follows:

The characteristics of the engine are a moment of inertia J_e, a viscous resistance coefficient δ_e, and an internal torque T_e. δ_e and T_e among them respectively indicate a partially linearized gradient and a generation torque when the engine rotation number is "0", in the rotation—torque characteristic in which a throttle divergence α_e, an atmospheric pressure p_e, and an air temperature t_e are inputted.

The characteristics of the transmission are a gear ratio N_m, a final gear ratio N_d, and a stiffness of an output axis C_P. Finally, the characteristics of the body are a tire radius R_T a mass of the body M_b, a resistance during running D_b, and an ascent of a running road θ. Since the characteristics of the body, R_T, M_b, and D_b are different according to the body structure or the like, they are required to be replaced according to the type of car.

Moreover, the control characteristic values of the engine control unit and the transmission control unit respectively controlling the engine and the transmission are preliminarily identified by the test data.

In order to perform a virtual test under the same condition as the car driving state by using the virtual prototype in Fig.41, the following model is further required. Firstly, for the gradient θ, the atmospheric pressure p_e, the air temperature t_e and the like, the environment condition model provided as an environment condition for using cars is required. Furthermore, for the throttle divergence α_e, and a gear ratio N_g of the transmission, the operation model which provides the driving operation condition of cars is required.

Finally, in order to evaluate the reproduction result of the virtual prototype in which the virtual test has been performed, the observation model for observing ω_e, v_b, T_e, f_b, and the like is required. The model for the conditions and for performing the evaluation is modeled based

on the evaluation test methods of the test standard models shown in Fig.40.

The virtual test performed by the model can be applied to various types of cars by incorporating the characteristic values of the body model which are different depending on the type of car into the virtual prototype of the functional part in the P/T which faithfully reproduces the characteristic value, performance, and behavior of the actual machine. The virtual test using the virtual prototype of the car model can be substituted for the various tests performed to various types of car on which the same P/T is mounted.

In the development of cars so far, the evaluation tests extending over a wide range have been performed to the cars having many body structures, so that the validity as a commodity has been verified. In such vast numbers of tests, the number of cars made on the experimental basis can be reduced and the development period required for the test can be shortened by the virtual test performed with the body characteristic value in the virtual prototype being replaced and with modeled test standard groups being combined. As a result, cost for a development can be reduced.

5. 3 Virtual testing system (model)

The basic arrangement of the actual machine test and the identification as well as the virtual test by the virtual prototype can be shown as in Fig.42.

It has been already described for the virtual test of the virtual prototype that the tested model which forms a subject of the actual machine test can be converted into the test model, the test standard can be modeled as the driving operation model and the environment condition model, and the execution result of the virtual prototype can be modeled as the observation model.

It is possible to compare and evaluate both of the observation data reproduced by the virtual test and the test data of the actual

68

machine test and to perform the identification. This indicates that the virtual test model and the test model for the identification can be made common.

Namely, the virtual testing system (model) can have consistency of the actual machine test, the identification, and the virtual test by incorporating an identification model 9 (corresponding to a calculation unit in Fig.38) which models the identification technique and process to update the internal characteristic value of the virtual prototype, and an evaluation model 35 in which the virtual test verifies the validity of the reproduction data.

In Fig.42, the actual machine test data are inputted to the evaluation model and to the identification model, and the result of the evaluation model is inputted to be related. As for both models, the following processes are performed: In case a problem arises in the result of the success/failure judgment in the virtual test, the former performs the actual machine test to evaluate again as shown in a dotted line, and in case there is a problem in the identification result of the virtual prototype, the latter can perform the identification again.

Main contents of each portion in the virtual testing system shown in Fig.42 are given as follows:

① The virtual prototype 1 corresponds to the motor model in Fig.38, and a model which reproduces the function, the performance, and the characteristic value of the product and part, which is composed of a mechanical system model relating to the mechanism and the structure, and the control system model for controlling them.

② A driving operation model 31 is a model for operating the virtual prototype 1 by the same driving condition as the actual machine. For example, there are an accelerator operation, a transmission operation, a braking operation of a car, and the like.

③ An environment condition model 32 is a model for reproducing the influence of the environment with the virtual prototype 1 being made

69

operate under the same condition as the environment for using the actual machine. For example, there are a running road, a temperature, a humidity, an atmospheric pressure, and the like when the car makes a market running.

5 ④ An observation model 23 is a model for reproducing the data, on the model, at each measurement point measured in the actual machine test as shown in Fig.38, so that the data which are difficult to be measured in an actual machine can be observed on the model.

⑤ An internal characteristic update model 24 is a model for updating
10 the internal characteristic value of the virtual prototype based on the identification result, as shown in Fig.38.

⑥ An actual machine test portion 33 performs a test which has been performed in the prior art, and a measurement unit 34 in the actual machine test portion 33 shows a unit for taking the test data into a
15 computer on real time basis.

The above-mentioned operation can be summed up as follows: If the driving operation condition and the environment condition are provided to the virtual prototype 1 from the models 31 and 32 respectively, the virtual prototype 1 provides the reproduction data
20 obtained as a result of the simulation at this time to the evaluation model 35 from the observation model 23. The evaluation model 35 evaluates, instead of the actual machine test, whether or not the reproduction data of the simulation result is valid (validity of product/part) by comparing the evaluation reference determined by the
25 test standard with the reproduction data.

In case of a failed evaluation, the evaluation model 35 instructs the virtual test portion 30 to change the driving operation condition and the environment condition, and to conduct the identification again if the deviation between the actual machine test data and the
30 reproduction data is large. Thus, as shown in the dotted line in Fig.42, the driving operation condition and the environment condition are

70

respectively provided to the actual machine test portion 33 from the models 31 and 32.

Accordingly, if the deviation between the actual machine test data from the actual machine test portion 33 through the measurement unit 34 and the reproduction data is large, the evaluation model 35 instructs the identification model 9 to conduct the identification again. Since the identification model 9 corrects the internal characteristic value of the virtual prototype 1 by the internal characteristic update model 34 after receiving the actual machine test data, the evaluation is performed again at the evaluation model 35 through the observation model 23. As a result, the identification model 9 updates the internal characteristic value of the virtual prototype 1 so that the deviation between the actual machine test data and the reproduction data becomes least.

When the evaluation ends, another modification (e.g. modification according to a type of car) in the virtual prototype 1 is evaluated. Particularly, by performing the identification to the internal characteristic value (control parameter) of the control model in the virtual prototype, the virtual prototype 1 can be tuned, according to the type of car, to an optimum state.

5. 4 Actual machine test of transmission applying virtual test

In case the actual machine test is performed to a unit of the functional part of the tested object, the functional part of the drive system for driving the part and the functional part of the load system which forms the load are required. The method in which the virtual prototype where such a drive system functional part and a load system functional part are identified is incorporated into the testing unit, and the actual machine test of the tested object is performed will now be examined.

Fig.43 shows an example of a testing unit of a transmission included in the virtual prototype.

71

Fig.43 shows a unit for reproducing the drive characteristic of the engine and the load characteristic of the car by the drive motor and the load generator, and for performing the actual machine test to the transmission proper along the actual use state. This unit derives the

5   performance required for the running of the car from the engine performance which forms the drive source, and the evaluate test about various performances relating to the acceleration such as an acceleration performance or a gearshift shock is performed by the actual machine.

10   In Fig.43, the testing unit 33 is composed of the drive motor 4 for driving the transmission, the load generator 5 which forms the load, the electric load 6, and the measurement unit 8 for measuring the driving state. Also, to the testing unit 33 the virtual prototype 11 of the drive motor 4, the load generator 5 and the transmission 50 is

15   connected for reproducing the driving state of the car. The testing unit 33 comprises the drive system control unit 71 and the load system control unit 72 which faithfully reproduce the result at the drive motor 4 and the load generator 5.

These control units 71 and 72 provide the drive torque of the

20   engine to the transmission 50 by the drive motor 4, and reproduce the load torque provided to the transmission 50 through the body by the load generator 5 and the electric load 6. Both models of the drive motor 4 and the load generator 5 can reproduce the function, the performance, and the behavior of the engine and the body in the testing unit 33 by

25   the identified virtual prototype 11.

The virtual prototype in which these drive motor 4, transmission 50 and load generator 5 are modeled is shown in Fig.44. It is to be noted that the operation system models 31, 38, 39, and the environment system model 32 inputted to the transmission model 1 in

30   Fig.43 are the models of the test standard mentioned above. The former represents the model which inputs the driving operation

condition of the driver, and the latter inputs the environment condition such as an air temperature which influences the internal characteristic value of the transmission. Also, the observation system models 23, 37, and 40 are models for observing the state values inside the virtual prototypes.

The motor model 13 of the drive system in Fig.44 is composed of the models of the motor, the battery, the fixed current control respectively in Figs.6, 4A, and 30. It is to be noted that a part of the internal characteristic values of the motor model 13 are omitted for simplified description of the model. Similarly, on the load side, the load generator model 14 is composed of the braking resistance in Fig.4(1) and the electric load is composed of the braking resistance on the left side of Fig.13, where a part of the internal characteristic values is omitted.

In Fig.44, the angular velocity ω_e and the input torque T_e connecting the drive system motor model 13 and the transmission model 1 are provided as target values of the drive system control unit 71. Similarly, a velocity v_b and a drive force f_b of the load generator model 14 are provided as target values of the load system control unit 72. Also, the drive torque T_e of the drive motor 4 can be reproduced by controlling the control current I_{CNT} with the operation system from the fixed current control model in Fig.30 and by adjusting the current of the drive motor.

Also, the load torque of the load generator 5 can be reproduced by being changed into the braking resistance value through the operation system from the motor model of the braking test in Fig.13. Also, as for the load torque, the fixed current control model and its unit in the same Fig.30 as the drive motor may be incorporated instead of the braking resistance.

Moreover, into the testing unit 33 shown in Fig.43, the internal characteristic update model 24 is incorporated in which the evaluation

model (see Fig.42) provided in the calculation unit 9 evaluate a difference if generated between the test result of the transmission 50 and the reproduction result of the virtual prototype 11, and the identification model (see Fig.42) similarly provided in the calculation unit 9 identifies the internal characteristic value in the transmission model (virtual prototype) 1.

5. 5 Actual machine test example of power train (P/T) applying virtual test

An example will be examined in which the actual machine test of the P/T where the engine and the transmission, except the motor 4 on the drive side and the virtual prototype 13 and the drive system control unit 71 leading to the motor 4, are united is performed in the actual testing unit shown in Fig.43.

The example of the actual machine testing unit having the P/T and the load generator is shown in Fig.45.

In this example, the same P/T 51 is mounted on the bodies whose structures are different shown in Fig.41, and the actual machine test is performed to the various cars, so that the adaptability of the P/T 51 for the cars having the different body characteristic values is verified.

The virtual prototype 1 of the P/T 51 requires many kinds in which transmissions such as an automatic transmission, a manual transmission, and a continuously variable gear are combined in addition to kinds of motors such as a motor, a gasoline engine, and a diesel engine. Accordingly, these virtual prototypes 1 are replaced with a model replacement unit 25.

Also, the virtual prototype 1 of the P/T 51 has a control model for reproducing the software of the control unit of the engine and the transmission, so that the virtual prototype 1 can control the model of the virtual prototype 1 and can directly control the actual machine of the engine and the transmission through a control input/output unit 36.

74

Accordingly, when adaptability of the body performance reproduced at the actual machine P/T 51 and the load generator 5 is worsened, the internal characteristic value of the control model can be changed through an internal characteristic update unit 24. Then, the

5   measure effect is firstly confirmed in the virtual prototype 1, and secondly the adaptability is again evaluated by the actual machine test to be confirmed.

In case a low-speed region torque of engine mounted on a car whose body weight or running resistance is large is insufficient and the

10   starting acceleration power is insufficient, the control characteristic value of the control model is updated through the internal characteristic update unit 24 in order to improve the acceleration performance and increase the fuel amount at starting the acceleration. The measure effect of the control amount change and the bad influence

15   on the fuel-efficiency and the exhausted gas worried because of the increased amount are firstly confirmed by the virtual test in the simulation of the virtual prototype, and the actual machine evaluation test of the P/T 51 is finally performed by using the virtual testing unit.

By this process, the tests for reproducing bad influence which

20   examines the measure effect and many test items can be verified by the simulation of the virtual prototype in a short time, so that it becomes possible to define the actual test items requiring a long time based on the verification result, and to perform an efficient test operation.

25   As described above, a characteristic value identification method and an apparatus therefor according to the present invention is arranged so that a functional model of a part is prepared based on a potential quantity and a flow quantity representing a strength and a quantity of energy applied to the part, a steady internal characteristic

30   value of the functional model in a steady state is identified, and a transient internal characteristic value of the functional model in a

75

transient state is identified by using the identified steady internal characteristic value. Therefore, the function of all of the articles which govern two dimensions of the potential quantity and the flow quantity prescribing the energy can be modeled.

5   Also, since the transient identification is performed to the internal characteristic value of the model after the steady identification, the steady identification without an interference of a transient state can be performed. Since the transient identification is performed based on the steady identification, there is an effect of

10   obtaining an accurate internal characteristic value by a simplified identification process. Also, it is possible to faithfully reproduce products/parts in the steady state and the transient state.

Moreover, by manufacturing an apparatus which uses such a characteristic value identification method, it becomes possible to

15   promptly perform the identification of the functional model of the same kind.

Furthermore, the characteristic value identification apparatus according to the present invention is arranged such that the functional model having the characteristic value identified by the identification

20   apparatus is incorporated in a virtual testing system as a virtual prototype, reproduction data are obtained from the virtual prototype by providing a driving operation condition and an environment condition, actual machine test data obtained by the driving operation condition and the environment condition are compared with the

25   reproduction data, and a re-identification is performed depending on the comparison result as the occasion demands. Therefore, it becomes possible to omit the actual machine test performed in a development process of a design, prototyping, and a test, to shorten a period, and to reduce cost for a development.